Energy Research and Development Division

FINAL PROJECT REPORT

On-Road Heavy-Duty Development, Integration, and Demonstration of Ultra-Low Emission Natural Gas Engines

California Energy Commission

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution, and transportation.

The California Energy Commission Research and Development Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. The Natural Gas Research and Development Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

On-Road Heavy Duty Development, Integration, and Demonstration of Ultra-Low Emission Natural Gas Engines is the final report for the Low NOx Natural Gas Engine Development for Heavy-Duty Vehicles project (Contract Number 500-12-012) conducted by the South Coast Air Quality Management District in conjunction with Cummins, Westport, Inc. The information from this project contributes to Energy Research and Development Division's Natural Gas Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The project team designed, developed and demonstrated production-intent ultra-low emissions 8.9 liter natural gas engines. The engines continued to utilize stoichiometric combustion with cooled exhaust gas recirculation and passive three-way catalyst as the current ISL G production engines, and added improved three-way catalyst, a closed crankcase ventilation system and optimized engine controls. The ultra-low emissions engine was named the "ISL G Near Zero".

The project team proved technical and commercial viability with the engine moving to full commercial production prior to the completion of the final project report. The California Air Resources Board certified the engine to their the Optional Low NOx 0.02g standards in addition to U.S. Environmental Protection Agency's current federal air quality and greenhouse gas emissions standards. These ultra-low emissions combined with the planned commercial availability will significantly reduce emissions from this on-road heavy-duty source category and assist the region in meeting federal ambient air quality standards in the future.

The engine was successfully demonstrated for on-road heavy-duty vehicle applications including transit buses and refuse trucks.

Keywords: ultra-low emissions, heavy-duty engine, Class 8, near zero

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Introduction

Heavy-duty on-road diesel vehicles are currently one of the largest sources of nitrous oxide (NOx) emissions in the South Coast Air Basin. This source category is projected as one of the largest contributors to nitrous oxide (NOx) emissions, even as the legacy fleet of older and higher polluting vehicles are retired from operation and replaced by the cleanest vehicles meeting the most stringent emission levels required by 2010 emissions standards. According to California's South Coast Air Quality Management District, developing ultra-low emissions natural gas engines would significantly reduce emissions from on-road heavy-duty diesel vehicles and help the region in meeting federal ambient air quality standards.

Cummins Westport Inc. (CWI) is a joint venture company between Cummins Inc. and Westport Innovations Inc. CWI develops and commercializes advanced, low-emissions, alternative fuel engines.

Project Purpose

The Cummins project team explored a natural gas engine suitable for on-road heavy-duty vehicle applications such as buses, refuse, goods movement, or drayage trucks or all of these. The heavy-duty diesel engines and associated exhaust after-treatment technologies must be commercially viable. The team designed, developed and demonstrated an ultra-low emission, commercially viable natural gas engine suitable for on-road heavy-duty vehicle applications. Additional technical objectives were to:

- Achieve emissions targets of 0.02 grams per brake horsepower-hour or lower as determined by the heavy duty engine federal test procedure (FTP),
- Keep exhaust ammonia (NH_3) emissions as low as achievable while targeting NH_3 emissions at 10 parts per million or lower,
- Be thermally and fuel efficient, incorporate methods to achieve minimal, or zero, fuel economy penalties relative to 2010 United States Environmental Protection Agency (EPA) and the California Air Resource Board (CARB)-certified diesel engines in similar duty cycle, and
- Be certified by the US EPA and CARB.

Project Process

The project team used CWI's existing commercial ISL G, 8.9 liter natural gas engine as a base to develop an ultra-low emission heavy-duty natural gas engine. The overall design strategy was to use the current ISL G engine and to evaluate changes or additions or both to components and software expected to contribute to achieving the target specifications. The team chose the current production ISL G base engine as the starting point including exploring several new technologies. Some of the technologies investigated were helpful and ready for quick implementation. Some were promising but potentially required a lengthy implementation timeframe, and some were not as useful as initially expected. Some technologies focused on fuel efficiency improvements while other concentrated on emissions reductions.

The team completed a risk analysis of these technologies to determine what components would work best to achieve the project goals, followed by combustion modeling and actual prototype engine data were used in simulations to predict fuel efficiency gains from the various engine and aftertreatment system improvements.

An engine and after-treatment technology design were developed based on simulation results. The after-treatment treated post-combustion gases after they leave the engine, reducing environmental impact without sacrificing power or performance.

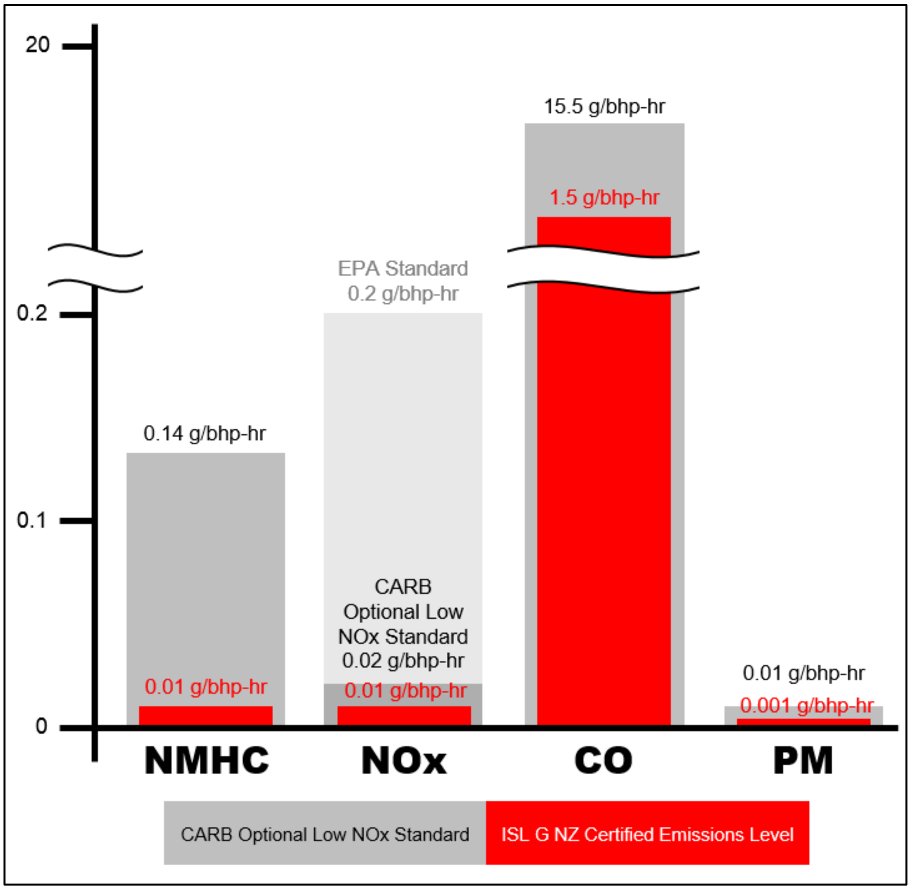
Using the emissions results from the simulation and testing of the engine and aftertreatment concepts and combined with estimates of component costs, reliability and other aspects, a system architecture was determined for the prototype engine and a pre-production engine was built for the initial tests. The engine was capable of reaching the near zero emissions targets while still meeting the original ISL G performance targets for horsepower and torque.

Lastly, the engine was tested and evaluated to see if any modifications were necessary to the engine configuration. No modifications were necessary. The team completed the dynamometer testing according to CARB regulations to measure emissions. The emissions certification approvals were received in late 2015 from CARB and EPA. The certification emissions results met the design targets and ARB issued two certificates, one for the urban bus service class and one for heavy-duty engines in the medium-heavy duty diesel service class.

Project Results

This new 8.9 liter heavy-duty natural gas engine, (ISL G Near Zero or ISL G NZ), successfully demonstrated emissions at or below CARB targets of 0.02 grams NOx, 0.14 grams nonmethane (nonnatural gas) hydrocarbons (NMHC), 0.01 particulate matter (PM), 15.5 carbon oxide (CO).

Figure ES-1: Emission Results



Source: Cummins Westport, Inc.

The new engine also successfully:

- Demonstrated a peak rating, or maximum power rating, of 320 horsepower and 1,000 ft per lb of torque, making the engine competitive with diesel engines of the same size
- Fuel consumption and mileage data from San Diego Transit Authority District indicated they were achieving 3.39 to 3.83 miles per gallon (MPG) for buses. University of California Riverside tests indicated the MPG on a diesel gallon equivalent assuming ranged from 4.5 MPG_e for the regional port cycle to 2.5 MPG_d for the central business district, or CBD cycle. The CBD cycle is one of several dynamometer tests completed for heavy-duty vehicles to measure emissions based on the driving pattern. In this case, the pattern is composed of idle, acceleration, cruise, and deceleration modes- known as a “sawtooth” driving pattern.
- In late 2015, CWI submitted and received emissions certification for the ISL G NZ from CARB (Optional Low NOx 0.02g standard) and USEPA (federal standard). The ISL G NZ engine reduces NOx more than 90 percent from current federal standards.

Benefits to California

The development and deployment of low NOx, advanced, and efficient natural gas vehicle technologies will lower greenhouse gas emissions and benefit natural gas ratepayers by improving air quality and reducing health and environmental risks associated with emissions from heavy-duty vehicles. Providing a low emission option to California's fleets is essential to meeting emission reduction goals in the state, particularly in regions where meeting Federal Ambien Air Quality Standards is difficult. In an effort to meet these standards, introducing a near-zero NOx emission engine that can be used in the heavy-duty sector will support efforts to reduce emissions in these regions.

The team exceeded the project's target goal of 90% NOx emission reductions and the technology has been commercially available since 2016. The ISL G NZ (renamed to L9N) is starting to replace the legacy ISL G 8.9-liter engine from which the ISL G NZ was developed from this project. So far, there are 709 ISL G NZ engines in California, and this number is expected to increase as fleets begin to replace older engines that no longer meet CARB emission standards. With the original ISL G 8.9-liter engine already accounting for approximately 46 percent and 36 percent of the refuse and transit markets respectively in California, it is estimated that the deployment of the near-zero engine developed under this project will reduce NOx emissions by approximately 2.2 tonnes per day in the South Coast Air Basin alone.

Lessons learned and near-zero engine development strategies developed paved the way for a larger 12-liter near-zero engine to be developed and commercially used. As of October 2018, 66 of the larger 12-liter engines are in service, with this number expected to increase as more incentives have become available for its purchase.

CHAPTER 1: Introduction

Background and Overview

Cummins Westport (CWI), is a joint venture company between Cummins Inc. and Westport Innovations Inc. CWI develops and markets the world's widest range of high performance low emissions engines for transit and commercial vehicles. CWI exclusively focuses on developing, commercializing, and supporting spark-ignited alternative fueled engines. CWI is the leading natural gas engine supplier in North America and for emission leading markets globally, and has established broad original equipment manufacturers (OEM) availability of CWI's engines. The proposed technology advancements and designs can be used and commercialized in CWI's product line creating an opportunity to leverage CWI's proposed work throughout North American commercial vehicle applications. Various industry stakeholders, including consultants, government agencies, and OEMs, are projecting significant natural gas vehicles in the North American heavy-duty commercial vehicle market, with some agencies forecasting 30 to 40% natural gas market share within the next decade.

Cummins Westport Inc. (CWI) proposed developing and demonstrating an advanced, production intent version of its 8.9-liter spark ignited natural gas engine and after treatment system, that would reduce NOx emissions 90% below 2010 CARB vehicle emission standards and improve thermal efficiency when compared to CWI's current production ISL G engine. The team would validate engine performance, reliability, durability, emissions, and manufacturability.

CWI assembled a comprehensive team of numerous industry leading organizations including Cummins Emission Solutions, Cummins Pacific, Autocar, Gillig, New Flyer, PACCAR, Waste Management, San Diego Transit and CR&R Environmental Services.

CWI began the project by assessing candidate technology advancements and design changes to reduce NOx and NH3 emissions and to improve thermal efficiency. CWI conducted a technical feasibility and risk assessment for each of the candidate technologies, filtering for promising and feasible technologies, and defined the architecture of the advanced ISL G engine and aftertreatment system.

CWI integrated the advanced, production-intent ISL G Near Zero engine into two engineering vehicles to validate the vehicle integration design and assess vehicle performance before customer vehicle demonstrations/field trials. CWI secured the support of the industry's leading OEMs in the Class 8 truck and transit bus markets, and leveraged their expertise and design guidance for the pre-commercial, production-intent engine, aftertreatment system, and vehicle designs.

CWI demonstrated the advanced, production-intent ISL G Near Zero engine and aftertreatment system in seven low cab forward refuse collection trucks, and six 40 foot buses operated by leading fleets in the South Coast and San Joaquin Valley Air Basins for a period extended past the original target of 12 months.

The CWI team anticipated proceeding to commercialize the advanced, production-intent ISL G Near Zero engine and aftertreatment system immediately following the end of the project. Because there was strong industry and market desire plus early success with technology development, CWI accelerated the commercialization process to run in parallel to this project to deliver the engine earlier than first anticipated.

Project Objectives

The objectives of this project were to:

- Achieve emissions targets of 0.02 grams per brake horsepower-hour (g/bhp·hr) NOx, 0.01 g/bhp·hr PM, 0.14 g/bhp·hr NMHC, and 15.5 g/bhp·hr CO or lower as determined by the heavy duty engine FTP,
- Keep exhaust NH_3 emissions as low as achievable while targeting NH_3 emissions at 10 ppm or lower,
- Be thermally and fuel efficient, incorporate methods to achieve minimal, or zero, fuel economy penalties relative to 2010 EPA and ARB certified diesel engines in similar duty cycle, and
- Be certified by the U.S. EPA and CARB.

Project Tasks

The Scope of Work for this project was structured into five tasks.

- Task 1 - Administration
- Task 2 – Development of Prototype Heavy-Duty Natural Gas Engine
- Task 3 – Engine Vehicle Chassis Integration
- Task 4 – Vehicle Demonstration Plan
- Task 5 – Technology Transfer Activities

The objectives and key work performed within the latter four of these tasks is described in the following chapters.

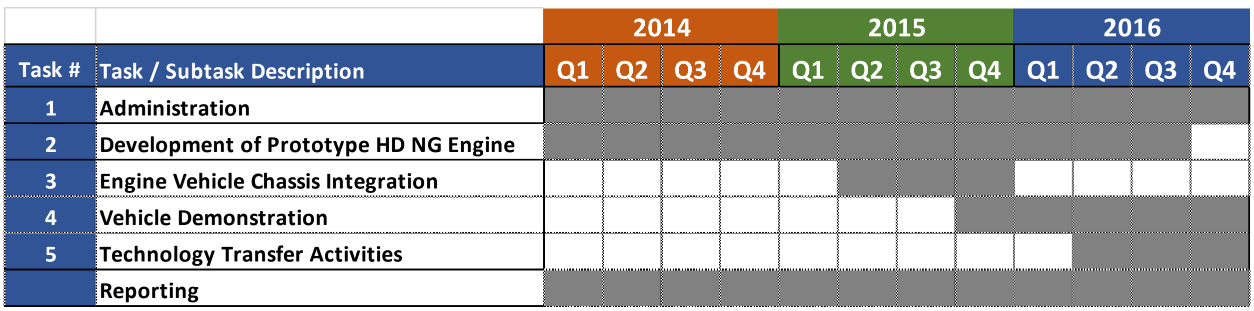
CHAPTER 2:
Use of Prototype Heavy-Duty Natural Gas Engine

Work Plan Development

The goal of this task was to develop a detailed work-plan for the design, analysis and development of the proposed natural gas engine and after-treatment technologies.

An overall work plan was developed for this project covering the development, integration and demonstration tasks along with reporting and technology transfer activities. A summary is shown in Figure 1.

Figure 1: Program Schedule



Source: Cummins Westport, Inc.

Specifications and Design Strategy

Overall key product target specifications were compiled to ensure this product would be well suited for on-road heavy-duty vehicle applications such as buses, refuse, goods movement, or drayage trucks or all of these. These target specifications were derived from the current ISL G product which is offered in all major vehicle OEMs for these market segments (Table 1).

Table 1: Key Product Target Specifications

Category	Product Target Specification
Emissions	NO_x = 0.02 g/hp-hr PM = 0.01 g/hp-hr NMHC = 0.14 g/hp-hr CO = 15.5 g/hp-hr GHG = 2017 GHG levels for application NH_3 = low as achievable, targeting 10 ppm
Reliability	New system does not compromise reliability
Power	Peak Power: 320 hp
Torque	Peak Torque: 1000 lb ft

Fuel Economy	No fuel economy penalties over current product
Operating Costs	No worse than current product
Maintenance Intervals	Minimize additional maintenance requirements
Transmission Compatibility	Same as current ISL G product

Source: Cummins Westport, Inc.

The overall design strategy was to use the current ISL G engine and to evaluate changes or additions or both to components and software expected to contribute to achieving the target specifications. Specifically, the current ISL G components not expected to help achieve the ultra-low emissions targets, were not studied further. These components included internal engine components (except piston and camshaft), engine head, intake and exhaust manifolds, cooled EGR system, and fuel system components.

The current production ISL G base engine was chosen as the starting point. Several new technologies were explored to meet the project goals. Some of the technologies investigated were helpful and ready for quick implementation. Some were promising but potentially required a lengthy implementation timeframe, and some were not as useful as initially expected. Some technologies were focused on fuel efficiency improvements while other concentrated on emissions reductions. A list of the most promising technologies used for the design strategy are shown grouped by engine design areas.

Air Handling

- Variable Geometry Turbo (VGT)

Engine/Combustion system

- Optimized camshaft
- Piston shape (circular round piston bowl)
- Piston material – gallery cooled steel

Ignition System

- Inductive ignition system (BeruTM coil + driver box)
- Exhaust manifold pressure (EMP) misfire detection

Fuel System

- Port fuel injection system (PFI)
- Skip fire (intermittent cylinder deactivation)

Catalyst

- Larger catalyst with new formulation
- Mid-bed heated exhaust gas oxygen (HEGO) sensor

Sensing and Control

- Exhaust gas recirculation (EGR) & throttle
- 3 knock sensors in even numbered cylinder locations
- Calibration tuning
- Catalyst mid-bed (between bricks) HEGO sensor
- Wide band universal exhaust gas oxygen (UEGO) at catalyst inlet location
- Cold cycle strategies (cold start, motoring, idling)
- New lambda control strategies
- Closed crankcase ventilation system (CCV)

Feasibility and Risk Analysis

The risk analyses for the candidate new technologies were organized in a standard nine box matrix (Figure 2).

Figure 2: Nine-Box Risk Analysis for New Technologies

		Difficult / Long Lead Time To Resolve		
		High	Medium	Low
Criticality to the program	High		VGT	Catalyst new design Alpha 0/1 controls Bigger catalyst Vehicle air waste gate control Mid-brick HEGO Exit motoring strategies EGR bypass during motoring Throttle close during motoring Cold cycle strategies Ramp & jump strategies CCV
	Medium		Inductive ignition system Steel piston Port fuel injection	Wideband lambda sensor EMP misfire detection
	Low			Optimized camshaft

Source: Cummins Westport, Inc.

Mechanical Components

The risks for mechanical component changes can be considerable and generally are greater than risks for software or calibration changes. Mechanical components typically have long lead times associated with changes. The mechanical component changes evaluated in this project were a VGT system, the addition of closed crankcase ventilation (CCV) system, a new piston, a new camshaft, port fuel injection and three-way catalyst design changes. These were evaluated because they could be critical to meeting the project objectives and represented promised low or moderate risk due to technical difficulty or long implementation times.

A VGT would be a significant change to the ISL G system architecture (Figure 3). CWI has used a VGT system on a natural gas 9L engine in the past, but not on a stoichiometric cooled EGR engine. The modeling predicted fuel efficiency gains were possible with a VGT system with no impact on emissions, but further evaluation and a cost benefit analysis was performed which recommended against using a VGT and instead staying with the current wastegate turbocharger.

A new piston in an ISL G engine could have efficiency, emissions, and/or robustness benefits. CWI has designed several pistons for these engines and it seemed low technical risk, but high cost and a long development period. An example of a potential new piston design is shown in Figure 4. A change in piston design was not recommended due to long lead time and uncertain benefit to near zero NOx emissions.

Figure 3: Modeled Image of Variable Geometry Turbo

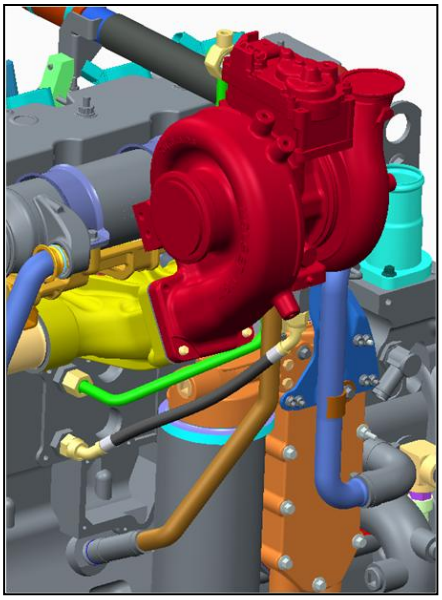
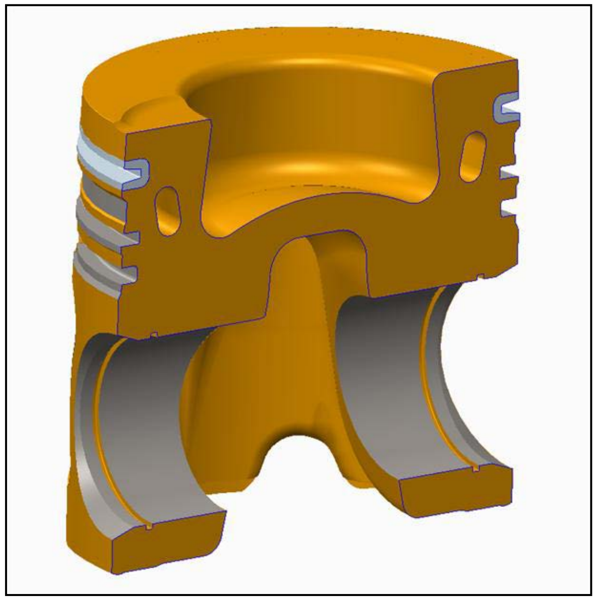


Figure 4: Cut Away of Potential New Piston Design

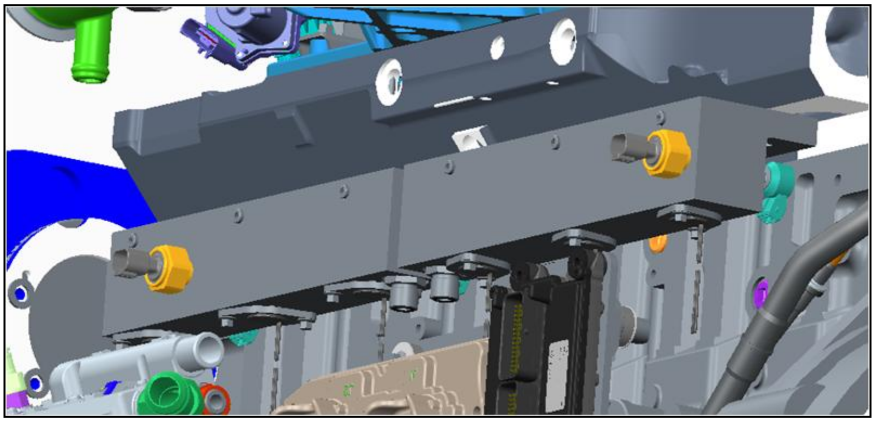


Source: Cummins Westport, Inc.

A new camshaft had potential for improved efficiency, emissions, and/or robustness. CWI had designed several camshafts for these engines and it was viewed as a low technical risk. However, a change in camshaft design was not recommended for further evaluation due to uncertain benefit to near zero NOx emissions.

Port fuel injection (PFI) is a significant change to the engine's fuel control strategy as well as the engine hardware. The technology has been used by other alternative fuel engine manufactures, indicating it is capable of providing improved emissions and fuel economy. The benefit of port fuel injection still needed to be demonstrated on an ISL G engine and evaluated in terms of cost, effect on vehicle integration, and time for implementation. A prototype PFI setup shown in Figure 5 was tested with minimal benefit towards near zero NOx emissions.

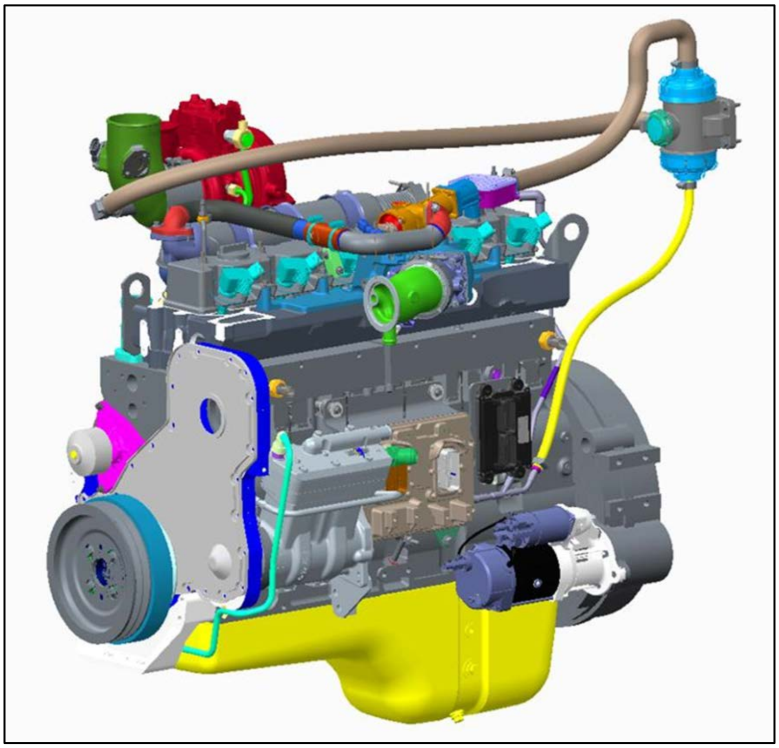
Figure 5: Prototype Port Fuel Injection System



Source: Cummins Westport, Inc.

The Closed Crankcase Ventilation (CCV) system was a low risk addition to the engine as a similar system was already in production on the Euro 6 version of the ISL G engine. CWI had experience with the performance and cost of this system on this engine. The CCV provided a significant reduction of crankcase methane emissions. A prototype CCV system is shown in Figure 6.

Figure 6: Engine Model with Prototype CCV System

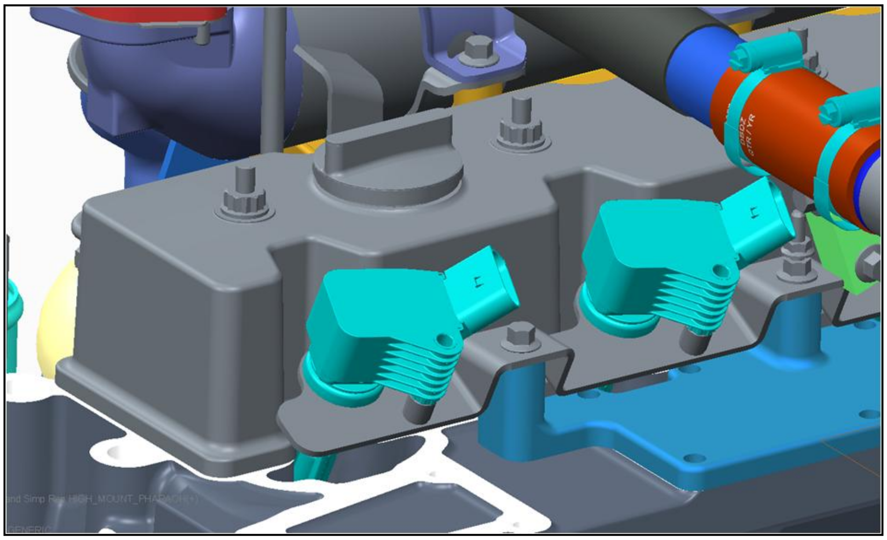


Source: Cummins Westport, Inc.

Engine Control System

The engine's control system was key to making the most of the hardware changes. The team investigated a new inductive ignition system. The inductive ignition system potentially offered improved fuel efficiency and less risk of misfire through more accurate and reliable spark control. This potential change was relatively low risk as the current ISL G ignition system would be used if the new system did not demonstrate an acceptable level of performance. A mockup of the new inductive ignition system is shown in Figure 7.

Figure 7: Mockup of an Inductive Ignition System



Source: Cummins Westport, Inc.

Sensor changes to the engine and aftertreatment system were evaluated. The necessary changes to demonstrate a controls benefit over the current product sensor package.

Calibration tuning and software changes were critical to the success of this product. The changes impacted performance, emissions, fuel economy, and durability of the engine. The risk level was low for these changes as the CWI engineering team dedicated to this area had extensive experience with other CWI commercial products and had identified key areas where improved performance was expected. Calibration and tuning improvements were expected to reduce NOx by reducing deviations from stoichiometric conditions, particularly during throttle transitions.

Aftertreatment Technology

This project continued to use stoichiometric, cooled EGR, spark ignited combustion, which is currently used on all CWI North American engines. The lack of excess oxygen in the exhaust from stoichiometric combustion allowed for the use of a three-way catalyst (TWC) aftertreatment. Compared to other aftertreatment options such as Selective Catalytic Reduction (SCR), TWC provides the customer with a simple, effective, maintenance free and efficiently packaged solution.

The intent of this project was to continue to use well established TWC technology for the aftertreatment and use the same supplier to develop an improved, higher performing version of the catalyst than the current product ISL G aftertreatment. Washcoat (a carrier for a precious metal catalyst), precious metal loading, sizing and installation location were all tested. The risk was relatively low for these changes given our vast experience with this technology on all North American CWI engines. A representative image of a TWC is shown in Figure 8.

Figure 8: Typical Three-Way Catalyst Used on CWI Engines

Source: Cummins Westport, Inc.

Engine/Vehicle Interface and Packaging

The current product ISL G was used as the starting point for this project. Since the ISL G was integrated into every major OEM for the North American Refuse and Transit market, as well as a wide selection of Medium Heavy Duty Tractor and Type D School Bus OEM's, there was significant knowledge and decisions derived from the existing vehicle integration. The engine packaging requirements was likely to be very similar to the current ISL G engine. Specific fit checks for components that changed from an ISL G engine needed to be performed for production, although the approximate spatial envelope wasn't expected to be impacted.

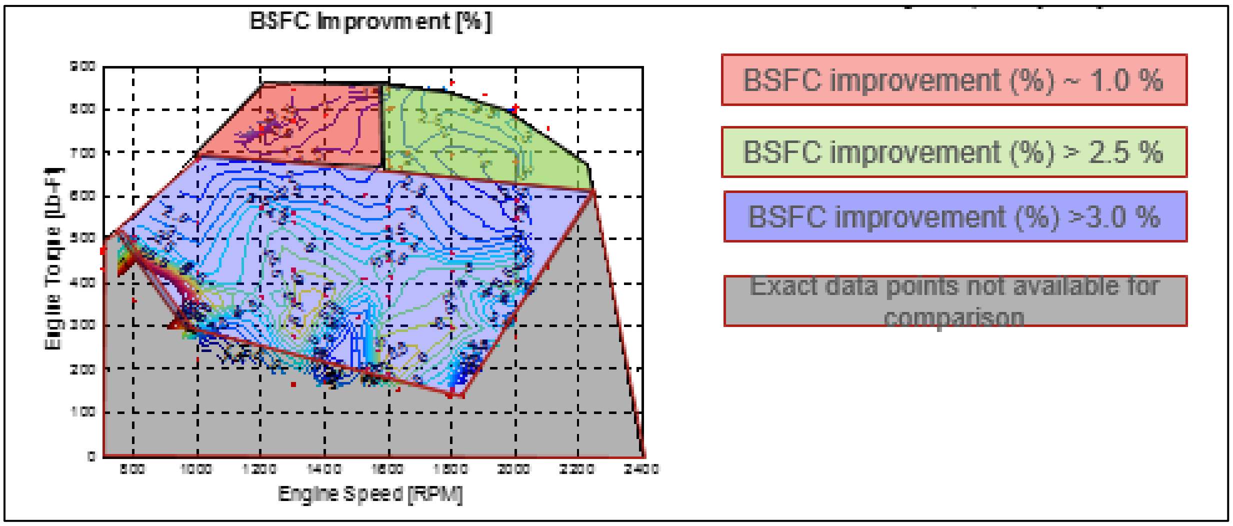
Emission Certification Targets

The emissions targets for the project were a 90% reduction in NOx from the current EPA/CARB standard while the other constituents (PM, NMHC, and CO) were the same as the current standard. The target for ammonia, which was not regulated by the EPA and CARB, was as low as achievable with a stretch target of 10 ppm. While the precedent setting NOx reduction would be challenging, based on the starting point of the current ISL G and preliminary capability assessments of the engine development areas listed above, there was high confidence a target of 0.02 g/bhp hr could be achieved. Initial expectations were that NH_3 emissions may deteriorate with the improvement in NOx emissions, but early assessments of aftertreatment elements and calibration tuning indicated a significant reduction in NH_3 emissions was possible without sacrificing other emissions. Overall there was a low risk that the emissions targets of this project could not be achieved.

Conceptual Testing, Analysis or Simulation

Simulations were done using GT Power combustion modeling and actual prototype engine data to predict fuel efficiency gains from the various engine and aftertreatment system improvements discussed above. Initial simulation results of the comparative brake specific fuel consumption (BSFC) fuel map using a combination of all of the technologies previously discussed is shown in Figure 9. A net positive fuel efficiency improvement could be achieved by implementing all of the technologies investigated, although other factors such as development time, reliability and cost needed to be evaluated to determine an overall “optimal” system architecture. For example, a variable geometry turbocharger would provide fuel efficiency improvements over the existing wastegate turbocharger but it would also require significant time to fully develop and validate for production.

Figure 9: Initial Simulation of BSFC Improvement



Source: Cummins Westport, Inc.

Simulations for emissions reductions were more challenging and required prototype testing to validate the simulation results. Aftertreatment, software, and calibration changes were required to work together to achieve 90% reduction in NOx emissions.

Engine and After-Treatment Technology Design

Multiple catalyst designs were tested. Three different close-coupled catalysts (CCC) were tested (specifically without an underbody catalyst) and one CCC was tested with an underbody catalyst present. Figure 10 shows a photo of one of these CCC’s. Price, availability, and performance determined the recommended catalyst architecture. The CCC was determined to be unnecessary to meet the near zero NOx target.

Figure 10: One of the Four Close Coupled Catalysts Tested

Source: Cummins Westport, Inc.

Using the emissions results from the simulation and testing of the engine and aftertreatment concepts and combined with estimates of component costs, reliability and other aspects, a system architecture was determined for the prototype engine. Table 2 summarizes the architecture.

Table 2: Recommended Engine and Aftertreatment Architecture

Engine Area	Recommended Architecture
Base Engine	Current product ISL G
Power Cylinder	No change
Intake Manifold	No change
Exhaust Manifold	No change
Cylinder Head	No change
Turbo	No change (continue with Wastegate Turbo)
Fuel Injection System	No change (continue with central point injection)
Crankcase Ventilation	Closed Crankcase Ventilation
Exhaust Gas Recirculation	No change
Engine Control Module	No change
Ignition Control Module	No change
Sensors	Addition of CCV pressure sensor, mid catalyst temperature sensor
Actuators / Valves	No change
Ignition System	No change
Engine Control Software	Implementation of various control strategies
Diagnostics	Engine Manufactures Diagnostics (EMD+) which is the first stage in implementing full Heavy Duty On-Board Diagnostics
Chassis Electronic Interface	No change
Aftertreatment	Single TWC with changes to size and material

Source: Cummins Westport, Inc.

Establishing Product Validation Matrix

An initial product validation matrix was created (shown in Table 3) to show the various engine areas and their progress through the product design process. The matrix was regularly updated in the progress reports throughout this project to represent the then current status. The typical engine product design process starts with developing the technology architecture followed by validating this technology. The result of this portion is a stable system architecture. From this point the component design can be completed and followed by validation of the design. Completion of this portion results in a stable engine design. The next step is to iterate the design if necessary and validate for stable performance. This project will end with stable performance and it should be recognized that further work to establish stable process is still required to bring the technology and product to commercialization.

Table 3: Initial Product Validation Matrix

		Stable Architecture		Stable Design		Stable Performance	
	Hardware / Software	Technology Architecture Development	Conceptual Validation	Alpha Design	Alpha Testing	Beta Design	Beta Testing
Engine Mechanical Components	Base Engine						
	Power Cylinder						
	Intake Manifold						
	Exhaust Manifold						
	Cylinder Head						
	Turbo						
	Fuel System						
	Crankcase Ventilation						
	Exhaust Gas Recirculation						
Engine Control System	Engine Control Module						
	Ignition Control Module						
	Sensors						
	Actuators / Valves						
	Ignition System						
	Engine Control Software						
	Diagnostics (EMD+)						
	Chassis Electronic Interface						
	Aftertreatment						

Source: Cummins Westport, Inc.

Build Prototype Engine and Exhaust After-Treatment Technology for Initial Laboratory Testing

Based on the engine and aftertreatment architecture designed in Task 2.3, a pre-production engine was built for the initial tests. The engine was capable of reaching the near zero emissions targets while still meeting the original ISL G performance targets for horsepower and torque. Engine acceleration of the low NOx engine and aftertreatment system, referred to as ISL G NZ looked similar to the engine acceleration on the current product ISL G engine.

Of the potential hardware changes investigated some were not critical to reaching emissions targets while maintaining expected engine performance including VGT, camshaft, port fuel injection, and close coupled catalyst. The changes necessary to be tuned for acceptable performance while reaching the targeted emissions included software, controls, catalyst, and calibration changes.

The production intent changes from a current ISL G engine were adding a CCV system (Figure 11), using a different larger 3-way catalyst (Figure 12) with the addition of a mid-bed temperature sensor, and software and calibration changes.

Figure 11: Prototype CCV System

Source: Cummins Westport, Inc.

Figure 12: Prototype Larger TWC

Source: Cummins Westport, Inc.

Build Production Intent Engine and Aftertreatment system for Final Performance & Emissions Validation

Build and Modify Engine

Three Alpha engines were built. The engines were used to demonstrate the performance and emissions capabilities of the ISL G NZ engine. All three engines were used to collect pre-certification emissions data and one of the engines was used for the official certification tests.

Calibrations for Performance Specifications

An important design target was to have similar performance to the current ISL G engine. Two measures of performance are engine acceleration rate and maximum torque over the nominal engine speed range. Acceleration rate is measured by the torque developed at constant speeds 1 and 2 seconds after a snap opening of the throttle. Intermediate and final torque values of the ISL G NZ and aftertreatment system were similar to those for the current product ISL G engine as shown in Figures 13a and 13b.

Engine performance was also evaluated on FTP (Federal Test Procedure) emissions cycles and Lug cycles (where the engine is operated on the torque curve starting at a low engine speed and increased at different rates) with comparison curves for the current product ISL G and the ISL G NZ shown in Figure 14a and 14b. These plots were derived from the speed and torque data generated during the FTP and show engine speed acceleration rate at individual speed/torque points. The engine torque from the current ISL G engine and the ISL G NZ engine were nearly identical.

Performance of the ISL G NZ was also evaluated in field test and chassis dyno testing during the demonstration phase.

Figure 13a: Current Production ISL G Torque Curve

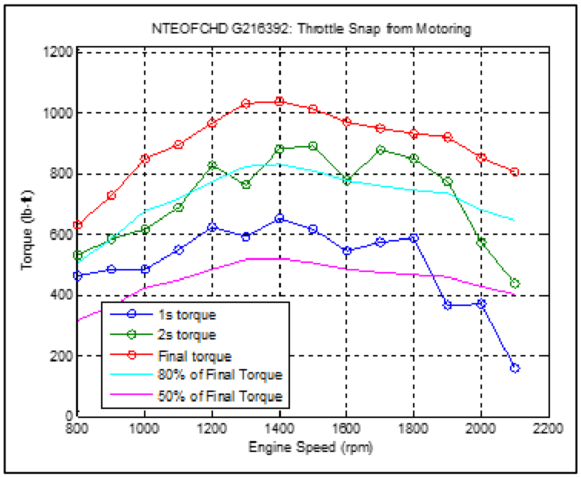


Figure 13b: ISL G NZ Torque Curve

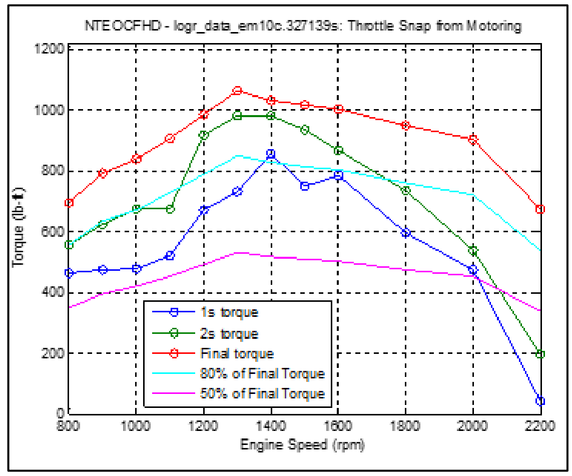


Figure 14a: Current Production ISL G Torque Curve

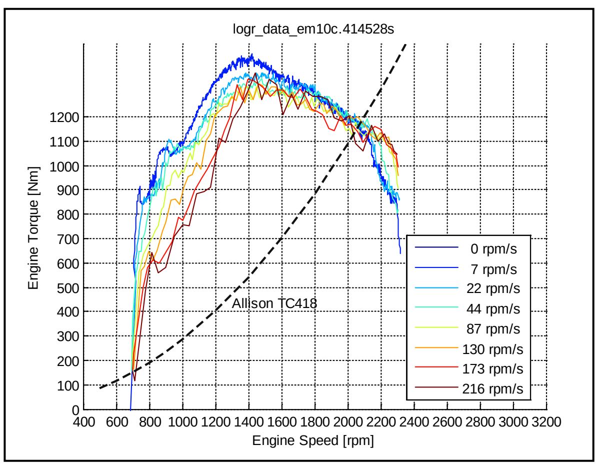
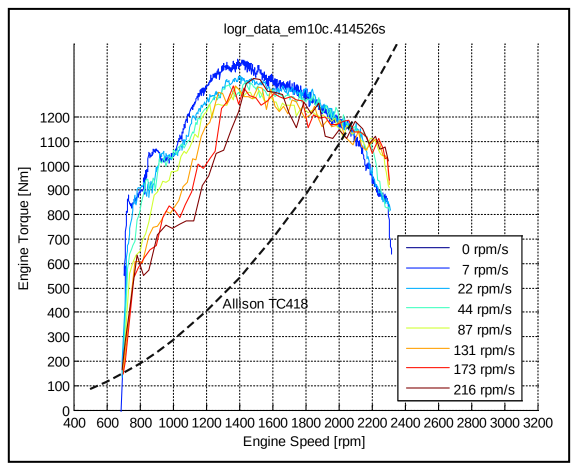


Figure 14b: ISL G NZ Torque Curve



Source: Cummins Westport, Inc.

Identify, Evaluate & Review Prototype Specification Changes

There were no changes from the prototype configuration to the production-intent engine. The changes for the ISL G NZ engine from the current ISL G 0.2 g/bhp·hr NOx engine are:

- A new larger and heavier three-way catalyst with mid-bed temperature sensor.
- A new closed crankcase ventilation system heated by coolant and mounted off engine. The CCV system has a breather element that must be changed after every 2000 hours of engine operation.

- A new impactor breather with integral crankcase pressure sensor.
- A new engine wiring harness to accommodate the crankcase pressure sensor as well as product robustness improvements.
- A new vehicle OEM wiring harness to accommodate a second temperature sensor on the new aftertreatment.
- Unique controls logic, software, and calibration are used on the ISL G NZ engine.

U.S. EPA Heavy Duty On-Highway Engine Dyno Test

Transient dynamometer tests per the EPA heavy-duty on-highway FTP duty cycle were performed to determine BSFC and NMHC, NOx, CO, PM, NH_3, N_2O, NO_2, CO2, and ultrafine emissions from the production-intent system, both pre- and post-exhaust after-treatment. The tests were the Cold/Hot Emission Test (CHET) which weights cold and hot cycles by one and six, respectively. The testing was conducted using natural gas that was laboratory tested according to Task 1.4 to confirm its adherence to the specifications in California Code of Regulation (CCR) Title 13 Section 2292.5. Data was subsequently submitted to the California Air Resources Board (CARB) and U.S. Environmental Protection Agency (EPA) for certification.

The emissions certification approvals were received in late 2015 from CARB and EPA. The certification emissions results met the design targets including 0.02 g/bhphr NOx. ARB issued two certificates, one for the urban bus service class (A-021-0629) and one for heavy duty engines in the medium-heavy duty diesel service class (A-021-0630). Figure 15 shows the data section from both CARB emission certificates. NH3 is not regulated by EPA or CARB, however, CWI has internal targets for NH3 on CHET cycles. The CWI ammonia target was met, however, the 10 ppm goal in the development project was not be met by the certified configuration. Table 4 summarizes criteria emissions results.

Figure 15: CARB Emissions Certification Results

MODEL YEAR	ENGINE FAMILY	ENGINE SIZES (L)	FUEL TYPE [1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS [2]	ECS & SPECIAL FEATURES [3]	DIAGNOSTIC [6]
2016	GCEXH0540LBI	8.9	CNG/LNG	Diesel	UB	TBI, TC, CAC, ECM, EGR, TWC, HO2S	EMD+

PRIMARY ENGINE'S IDLE EMISSIONS CONTROL [5]	ADDITIONAL IDLE EMISSIONS CONTROL [5]
EXEMPT	N/A

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
8.9	ISL G 250 / 4836;FR95359 (258), ISL G 280 / 4836;FR95354 (280), ISL G 300 / 4836;FR95351 (300), ISL G 320 / 4836;FR95348 (320)

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.02	0.02	*	*	15.5	15.5	0.01	0.01	*	*
CERT	0.01	0.000	0.01	0.004	*	*	1.5	0.3	0.001	0.000	*	*
NTE	0.21		0.03		*		19.4		0.02		*	

[4] g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET= Supplemental emissions testing; NTE=Not-to-Exceed; STD=standard or emission test cap; FEL=family emission limit; CERT=certification level; NMHC/HC=non-methane/hydrocarbon; NOx=oxides of nitrogen; CO=carbon monoxide; PM=particulate matter; HCHO=formaldehyde

In g/bhp-hr	EPA CERTIFICATE OF CONFORMITY		PRIMARY INTENDED SERVICE CLASS	
	*		VOCATIONAL	
	CO_2		CH_4	N_2O
	FTP	SET		
STD	555	*	0.10	0.10
FCL	476	*	*	*
FEL	490	*	0.65	*
CERT	465	*	0.56	0.02

4 g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET=Supplemental emissions testing; STD = standard or emission test cap; FEL=family emission limit; FCL=family certification level; CERT=certification level; CO_2=carbon dioxide; CH_4=methane; N_2O=nitrous oxide; VOCATIONAL=vocational engine; TRACTOR=tractor engine

Source: Cummins Westport, Inc.

Table 4: Summary Engine Emissions Test Results

	BSNOx	**BSCO**	**BSNMHC**	**BSPM**	**BSCO2**	**NH3**	**BSCH4**	**GHG HHD Vocational**	**GHG MHD Tractor**
	g/hp-hr	**g/hp-hr**	**g/hp-hr**	**g/hp-hr**	**g/hp-hr**	**ppm**	**g/hp-hr**	**g/hp-hr**	**g/hp-hr**
CARB Standard	**0.02**	**15.5**	**0.14**	**0.01**				**555**	**487**
Design Target	0.01298	7.92	0.065	0.0057		125	0.75	534	468
CHET 1	0.0078	0.92	0.0045	0.0007	465	87	0.54	479	
CHET 2	0.0085	0.85	0.0065	0.0000	456	66	0.42	466	
RMCSET	0.033	0.21	0.0000	0.0003	415	61	0.31		425

Test #	**BSNOx (g/hp-hr)**	**BSHC (g/hp-hr)**	**BSCO (g/hp-hr)**	**BSCO2 (g/hp-hr)**	**CBECM**	**Comments**	**Work (hp-hr)**	**BSFC (g/hp-hr)**
G398240	0.0448	1.18723	2.26474	485.688	0.40812	True Cold	24.3207	180.20
G398241	0.0018	0.42141	0.69922	462.06	0.61455	WFTP	24.6834	170.13
G398244	0.0033	0.29476	0.21206	414.531	2.44227	RMCSET	106.983	154.08
G398280	0.0429	1.04567	2.11594	469.239	3.83365	ColdFTP	24.3784	178.83
G398281	0.0029	0.31522	0.64334	453.456	2.77444	WFTP	24.7352	169.30

Source: Cummins Westport, Inc.

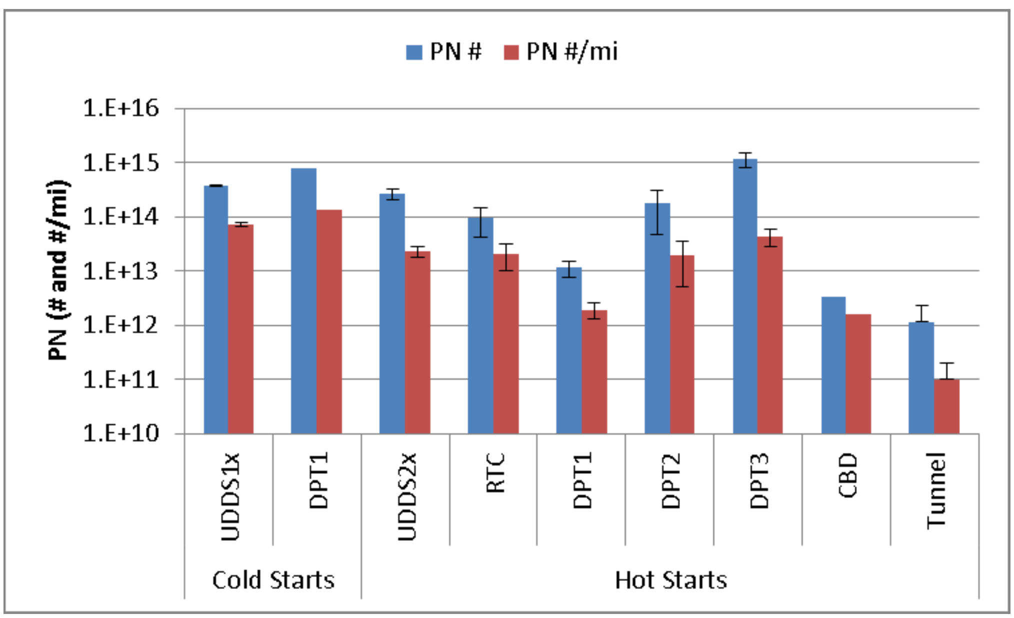
Ultrafine particulate emissions were measured using the Particle Number procedure described in the Euro 6 legislation. This data was collected during the pre-certification testing and is shown in Table 5. Particle Number data was also collected during the chassis dyno testing and is shown in Figure 16.

Table 5: Particulate Number Emissions

Calibrations	Cal Change	FTIR NOX	NOx	CH4	NMHC	CO	PM	PN	NH3	BSCO2	GHG	BSFC	BSHC
			g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	#/hp-hr		g/hp-hr	g/hp-hr		g/hp-hr
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	ST Retard 20. New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and starts timer of		**We are running 2000 SCFM for Tunnel flow from now on for Warm Cycles. As 1400 scfm was getting close to pegging**										
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	**SimCHET. ST Retard 20.** New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and		0.008076	0.362632	0.010389	0.927334	#VALUE!	**1.46126E+11**	0	452.7756	461.8414	#REF!	0.36299
			We are running 3250 SCFM for Tunnel flow from now on for SimCold and COLD cycles. As 3000 scfm was getting close										
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	**SimCHET. ST Retard 20.** New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and		0.004609	0.349626	0.006119	0.886661	-2.3E-05	**1.76506E+11**	95.76995	455.6294	464.37	0	0.346073
			PM Sampling Dilution Ratio Verification and PM Proportional Sampling Verification and Proportional Batch Sampling V										
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	**True CHET. ST Retard 20.** New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and		0.008274	0.493918	0.018256	0.917097	-5.8E-05	**1.81154E+11**	87.74469	457.8925	470.2405	0	0.498511
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	**RMCSET. ST Retard 20.** New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and		-0.00012	0.420107	#REF!	0.087445	0.000358	**2.94326E+11**	48.008	406.445	#REF!	#REF!	0.408836
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	ST Retard 20. New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and starts timer of												
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	**SimCHET. ST Retard 20.** New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and		0.007182	0.365998	0.009964	0.843942	0.000363	**1.437E+11**	95.0972	454.7594	463.9093	0	0.365838
			We had to re-run the Warm Cycle as it aborted after the cold cycle. So the official warm was run as follows, 1st we ran										
Z:\TC312\Gas\ISLG_PreCert_2015\73828301\Calibrations\New Software\Core_II_ICD.V25.43.43.107.aa_B_1TCC_Modified_ST 20_No_AL.xcal	**True CHET. ST Retard 20.** New Software - Cal Similar to B_1TCC. The Alpha 1 should not come on till cat temp reaches 300 deg C and		0.006808	0.358438	0.009861	0.823826	-0.00038	**2.00842E+11**	79.42149	454.3774	463.3383	0	0.358383

Source: Cummins Westport, Inc.

Figure 16: Particulate Number Emissions from Chassis Dyno Testing



Source: Cummins Westport, Inc.

Bottled fuel was used for the certification test because the ethane concentration in natural gas pipeline fuel was not reliably within the desired natural gas fuel specification. The bottle fuel came in cylinders targeting 4% ethane and 96% methane as shown by the copies of the three certificates of analysis in Figure 17.

Figure 17: Certificates of Analysis of Bottled Test Gas

Airgas

Airgas Specialty Gases

CERTIFICATE OF ANALYSIS
Grade of Product: PRECISION BLEND

Part Number:	X02ME96ECS3C0B5	Reference Number:	54-124501864-1
Cylinder Number:	GCB150	Cylinder Volume:	5764.5 CF
Laboratory:	ASG - Chicago - IL	Cylinder Pressure:	2398 PSIG
Analysis Date:	Jul 07, 2015	Valve Outlet:	350
Lot Number:	54-124501864-1		

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/or N.I.S.T. Gas Mixture reference materials.

ANALYTICAL RESULTS

Component	Req Conc	Actual Concentration (Mole %)	Analytical Uncertainty
ETHANE	4.000 %	3.861 %	+/- 2%
METHANE	Balance		

Notes: Propane: < 0.15 %
Butanes: < 0.10 %
Pentanes: < 0.01 %
C6+ < 0.01 %
Oxygen: < 0.01 %
Carbon Dioxide: 0.0094 %
Nitrogen: 0.078 %
Carbo

Approved for Release

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Airgas

Airgas Specialty Gases

CERTIFICATE OF ANALYSIS
Grade of Product: PRECISION BLEND

Part Number:	X02ME96ECS3C0B5	Reference Number:	54-124501864-1
Cylinder Number:	GCB160	Cylinder Volume:	5764.5 CF
Laboratory:	ASG - Chicago - IL	Cylinder Pressure:	2398 PSIG
Analysis Date:	Jul 07, 2015	Valve Outlet:	350
Lot Number:	54-124501864-1		

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/or N.I.S.T. Gas Mixture reference materials.

ANALYTICAL RESULTS

Component	Req Conc	Actual Concentration (Mole %)	Analytical Uncertainty
ETHANE	4.000 %	4.189 %	+/- 2%
METHANE	Balance		

Notes: Propane: < 0.15 %
Butanes: < 0.10 %
Pentanes: < 0.01 %
C6+ < 0.01 %
Oxygen: < 0.01 %
Carbon Dioxide: 0.0094 %
Nitrogen: 0.078 %
Carbo

Approved for Release

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Airgas

Airgas Specialty Gases

CERTIFICATE OF ANALYSIS
Grade of Product: PRECISION BLEND

Part Number:	X02ME96ECS3C0B5	Reference Number:	54-124501864-1
Cylinder Number:	GCB161	Cylinder Volume:	5764.5 CF
Laboratory:	ASG - Chicago - IL	Cylinder Pressure:	2398 PSIG
Analysis Date:	Jul 07, 2015	Valve Outlet:	350
Lot Number:	54-124501864-1		

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/or N.I.S.T. Gas Mixture reference materials.

ANALYTICAL RESULTS

Component	Req Conc	Actual Concentration (Mole %)	Analytical Uncertainty
ETHANE	4.000 %	4.056 %	+/- 2%
METHANE	Balance		

Notes: Propane: < 0.15 %
Butanes: < 0.10 %
Pentanes: < 0.01 %
C6+ < 0.01 %
Oxygen: < 0.01 %
Carbon Dioxide: 0.0094 %
Nitrogen: 0.078 %
Carbo

Approved for Release

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Source: Cummins, Inc.

Validation of Specifications

Testing of the chosen architecture and design, with changes to the crankcase pressure sensor, mid-bed catalyst temperature sensor, engine controls and aftertreatment, has shown stable performance as shown in the completed Product Validation matrix in Table 6.

Table 6: Product Validation Matrix

		Stable Architecture		Stable Design		Stable Performance	
	Hardware / Software	Technology Architecture Development	Conceptual Validation	Alpha Design	Alpha Testing	Beta Design	Beta Testing
Engine Mechanical Components	Base Engine	✓	✓	✓	✓	✓	✓
	Power Cylinder	✓	✓	✓	✓	✓	✓
	Intake Manifold	✓	✓	✓	✓	✓	✓
	Exhaust Manifold	✓	✓	✓	✓	✓	✓
	Cylinder Head	✓	✓	✓	✓	✓	✓
	Turbo	✓	✓	✓	✓	✓	✓
	Fuel System	✓	✓	✓	✓	✓	✓
	Crankcase Ventilation	✓	✓	✓	✓	✓	✓
	Exhaust Gas Recirculation	✓	✓	✓	✓	✓	✓
Engine Control System	Engine Control Module	✓	✓	✓	✓	✓	✓
	Ignition Control Module	✓	✓	✓	✓	✓	✓
	Sensors	✓	✓	✓	✓	✓	✓
	Actuators / Valves	✓	✓	✓	✓	✓	✓
	Ignition System	✓	✓	✓	✓	✓	✓
	Engine Control Software	✓	✓	✓	✓	✓	✓
	Diagnostics (EMD+)	✓	✓	✓	✓	✓	✓
	Chassis Electronic Interface	✓	✓	✓	✓	✓	✓
	Aftertreatment	✓	✓	✓	✓	✓	✓

Source: Cummins Westport, Inc.

Durability Test

This task called for a minimum of 250 hours of engine durability testing. The main avenue for durability testing was through vehicle field testing (Task 4). In addition to vehicle field testing, three engines were specifically built for this program's test cell testing. The engines were used for emissions development, product testing, and certification. The engines accumulated over 1,900 hours in the test cells as summarized in Table 7, well exceeding the project requirement of 250 hours. All test cell issues uncovered were captured and resolved using an internal Cummins development process referred to as FIRG (Failure Incident Report Group) which will be described in more in Task 4.3.

Table 7: Test Cell Testing Hours

ESN	Test Cell Hours
73828290	479
73828301	620
73837842	810
Total to Date	**1,909**

Source: Cummins Westport, Inc.

Emission Certification and Commercialization Pathway

The goal of the certification pathway was to identify the proposed path towards eventual emissions certification of the engine and exhaust after-treatment technology.

Certification Pathway

Typical engine and aftertreatment certification occurs after a lengthy technology development process followed by a product development process. During the technology development process, the focus is to identify the technology to be used in order to reach a set of product attributes which include targets for emissions, performance and costs. For this ultra-low emissions natural gas engine project, the technology / architecture chosen was stoichiometric, spark ignited combustion with cooled exhaust gas recirculation and a three-way catalyst.

Once the architecture was deemed stable, then the product development phase was undertaken to develop the commercial product meeting predetermined product attributes that not only include emissions, performance, and cost targets, but also product reliability and durability targets. Additional sociability (i.e. noise attributes) and serviceability (i.e. maintenance items) targets are added to the development goals. The product development phase follows a well-established process at Cummins referred to as Value Package Introduction (VPI) in order to increase the likelihood of a successful, quality product to the market.

Although the engine emissions are measured in some capacity right from the start of the project, the certification work is not initiated until the development has shown stable design and stable performance.

The certification pathway has specific actions dictated by the intended geographical market of the product, such as North America or Europe, although there are many common steps regardless of the geography. The Ultra-Low NOx product is intended for the North American market and is heavily driven by California's air quality issues and air quality improvement goals. Therefore, CARB and the EPA certifications were targeted. The target emissions level was CARB's Optional Low NOx 0.02g level.

The application of the product also dictates the certification pathway. The Ultra-Low NOx product is intended for on-road applications in heavy duty vehicles, and therefore an "On-Road

New Vehicle & Engine Certification Program" and "Heavy-Duty On-road engine" process were followed for CARB and EPA respectively. It should be noted that while CWI's ISL G is a spark ignited engine, EPA and CARB dictate the engine follows compression ignition engine rules.

Certification to California's emission standards for heavy-duty engines follows California Code of Regulation, Title 13 and the associated test procedures. Certifying to EPA emissions standards follows rules outlined in 40 CFR Part 86 (On-Highway Heavy-Duty Engines) according to Section 206 of the Clean Air Act (42 U.S.C. section 7525).

CARB and EPA certification processes require the engine and aftertreatment emissions to be measured in a test cell over two duty cycles; the first being the Federal Test Procedure (FTP) and the second being the Supplemental Emissions Test (SET). The FTP test is intended to simulate transient application of the engine while the SET is intended to simulate steady state operation of the engine. The emissions of interest and associated emission standard limit standard are shown in Table 8

Table 8: Targeted CARB and EPA Emissions and Limits

Emission Constituent	CARB / EPA Standard (g/bhp·hr)
Non-methane hydrocarbons (NMHC)	0.14
Oxides of Nitrogen (NOx)	0.02 (CARB Optional Low NOx 0.02 level)
Carbon Monoxide (CO)	15.5
Particulate Matter (PM)	0.01
Carbon Dioxide (CO_2)	576
Nitrogen Oxide (N_2O)	0.10
Methane (CH_4)	0.10

Source: Cummins Westport, Inc.

A number of different test cells were used to develop the calibration for ISL G NZ, but the certification test needs to occur in a test cell that meets EPA 1065 regulations. The Cummins emissions development group and Cummins test operations group at the Cummins Technical Center, in Columbus, Indiana, worked for about six months to prepare the test cell for the certification test. The test cell was already EPA 1065 compliant for a 0.20g NOx FEL, but additional work was required to ensure that the test cell could certify the 0.02g NOx engine. Tunnel dilution flow was optimized for the ISL G NZ engine. Analyzer precision and accuracy were scrutinized and all testing procedures were evaluated for the certification test.

Emissions testing is conducted over two duty cycles; the FTP which simulates heavy-duty transient operation and the SET which simulates heavy-duty steady state operation. Cummins engineering standard work document mandates that a minimum of three engines run a pre-certification test to help determine emissions variability. The emissions variability from the three pre-certification tests are used to determine an emissions design target for the certification test. The certification results must be at or below the emissions target before Cummins will allow the certification data to be submitted to CARB and EPA.

The data sent with a certification submission package includes the emissions data, greenhouse gas data, engine manufacturer diagnostics (EMD)+/on-board diagnostics (OBD) compliance data, and the Auxiliary Emission Control Device (AECD) and OBD documents.

Beyond CARB and EPA requirements for emission test data from a certified emissions test cell, CWI's internal development process requires the operation of field trial vehicles to ensure confidence with emissions results. A minimum of six field test vehicles must run for a minimum of six months and these vehicles must test the final production calibration for a period of at least eight consecutive weeks before it can be used in production. In addition to the field test vehicles, CWI uses at least one engineering vehicle to complete engineering tuning and other development tasks.

Commercialization Pathway

The goal of the commercialization pathway is to identify the proposed path towards eventual commercialization of the engine and exhaust after-treatment product.

As mentioned, product development follows a set procedure for designing, developing and introducing a new product to the market, referred to as value package introduction (VPI). This process ensures all areas of commercialization are addressed for a successful product in the market.

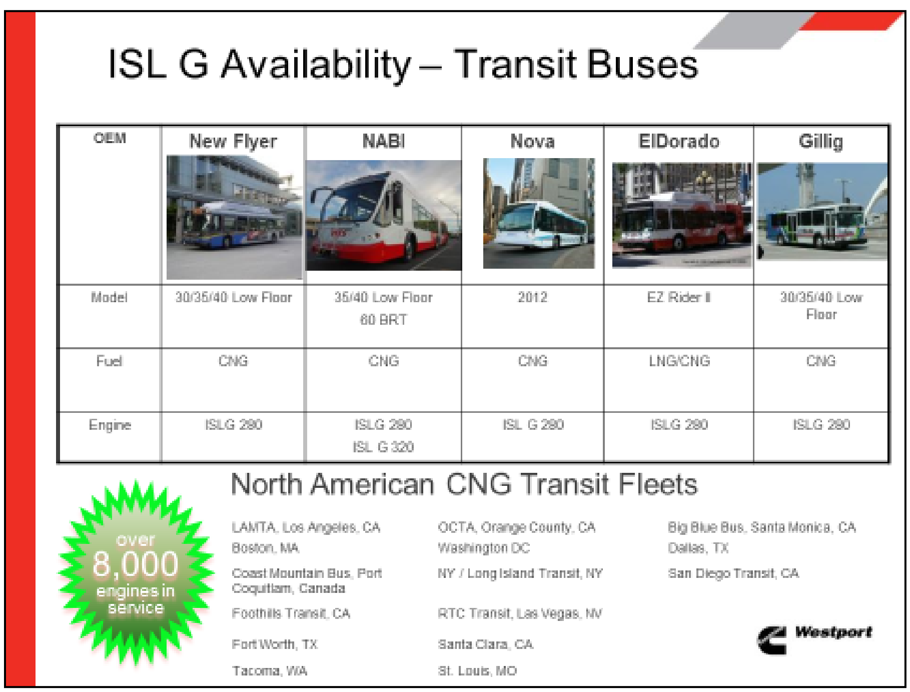
CWI is an engine OEM supplier and therefore the intended outcome of a product development project is to have a commercial engine and aftertreatment system that will be sold as "first fit" to vehicle OEM's and then offered in a complete vehicle to the end user / fleet. In addition to a "first fit" engine offering, CWI intends to offer the engine and aftertreatment through a "repower" option where an existing vehicle's engine is removed and replaced with a new Ultra-Low NOx engine (ISL G NZ) and aftertreatment. The Ultra-Low NOx project applied the technology to CWI's ISL G engine and therefore the ISL G NZ was expected to be offered to all current ISL G vehicle OEMs.

The ISL G engine was first introduced in 2007 meeting 2010 emissions ahead of requirements. Since 2007, this engine has become the alternative fuel engine of choice for the refuse and transit markets capturing approximately 46% and 33% market share respectively. The ISL G is available in all major vehicle OEMs and models in each of those market segments. Figures 18 and 19 provide a summary of the current ISL G availability in the Refuse and Transit market segments.

Figure 18: ISL G Availability in Refuse Market Segment

Source: Cummins Westport, Inc.

Figure 19: ISL G Availability in Transit Market Segment



Source: Cummins Westport, Inc.

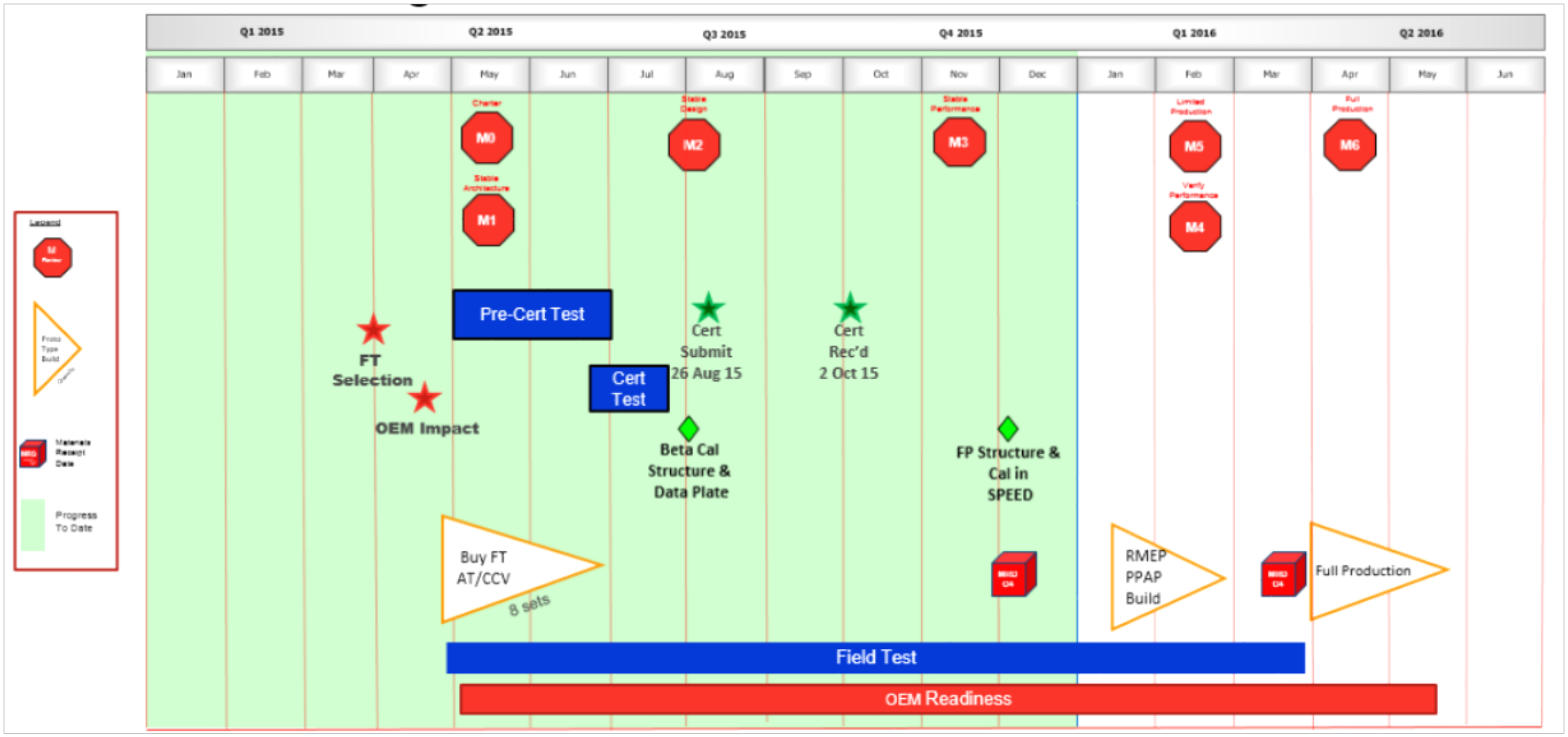
The VPI process addresses the necessary steps to ensure the technical, purchasing, manufacturing, customer engineering, marketing, customer care and finance areas are all ready for a commercial product launch. These streams mainly cover unique areas, although constant collaboration between areas is required throughout the development process to ensure the end product goals are met. The main functions of the streams are:

- *Technical* - addresses the technical attributes of the engine, ensuring the performance (specifically power and torque), reliability, and durability targets are met.
- *Purchasing* – establishes the suppliers and supplier agreements for the various engine components.
- *Manufacturing* – is typically the engine plant, which for the ISL G is the Cummins engine plant in Rocky Mount, North Carolina. Manufacturing is responsible for the engine production assembly and the “end of line” final test before the engine is shipped to the vehicle OEM.
- *Customer Engineering* – works with the vehicle OEMs to ensure the vehicle OEM understands the engine and aftertreatment integration requirements for mounting in the vehicle chassis. Customer engineering also relays any vehicle OEM requirements or special requests back to the engine design team, such as unique mounting brackets or positions for accessories.
- *Marketing* – is responsible for the initial voice of the customer/business/market to establish the product target attributes. Throughout the development process Marketing conveys the product message to the vehicle OEMs including typical marketing communication, sales training and ordering process. Mostly towards the end of the development process, Marketing increases the public communication, directed towards end users and other stakeholders.
- *Customer Care* – ensures the service and parts network is ready to support the engine post-launch including ensuring readiness at the Cummins distributors.
- *Finance* – throughout the development process finance is responsible for the program budget and forecasts the expected post launch business impact of the product.

The VPI process uses six gates to review the development progress in each of these areas compared to expectations in the development process. At each of these gates (M0 thru M6), a management review group is presented with the data from each function to show the expected work has been successfully completed. Only when deemed acceptable, the development program passes the gate and is allowed to continue with the next phase of development.

A new VPI program was launched in early 2015 with the goal of releasing a 0.02g NOx certified ISL G engine system for production in 2016. Outside of this funded project, although closely connected, the VPI program successfully launched the ISL G Near Zero engine and aftertreatment in mid-2016. A high level product development schedule is shown in Figure 20. In general terms, the development program must show stable design, followed by stable performance and then stable process. This ensures all of the streams above have completed their work which greatly increase the likelihood of a product that meets the customer's expectation not just in performance, but also with reliability, durability and overall cost of ownership.

Figure 20: ISL G NZ VPI Program Schedule



Source: Cummins Westport, Inc.

CHAPTER 3: Engine Vehicle Chassis Integration

Work Plan Development

The engine vehicle chassis integration work plan was developed with a retrofit approach in mind taking into consideration the current ISL G engine and its availability in a wide selection of vehicle chassis servicing the Truck, Refuse, Urban Bus and School Bus markets. This approach minimizes demonstration delivery time and optimize resources for this project. The retrofit approach refers to utilizing an existing production vehicle powered by an ISL G engine of specific recent vintage which allows for the addition of parts developed under the ultra-low emissions development phase of this project. A retrofit approach would not be an option for the commercial production version of the ISL G NZ due to the complexity and cost effectiveness of ensuring the correct engine and parts are used.

Specifications and Design Strategy

The ISL G NZ engine was aimed for the same market segments (Truck, Refuse, Urban Bus, and School Bus) through the same vehicle OEM's as the current ISL G engine. By using the current ISL G engine as the starting point for the technology development, the integration activities were greatly simplified and the integration and validation scope reduced compared to a brand new engine in an existing chassis. The strategy for engine vehicle integration of the ISL G NZ was based on the differences between the ISL G and the ISL G NZ engine and aftertreatment system. The fundamental specification was that the ISL G NZ engine and aftertreatment system must fit into the available space in the vehicle chassis. Since the vehicle chassis design is changed relatively infrequently, the integration work on the older demonstration vehicles would be applicable to many newly built OEM vehicles.

This project's integration design work is based on the Cummins process and procedures for the integration of an engine into a vehicle chassis for the first time, captured in application engineering bulletins (AEB) and installation quality audits. For this project, the demonstration vehicles were existing ISL G powered vehicles and therefore not all activities identified in the Cummins process were required. Task 2 described the engine and aftertreatment development work required to meet the performance and emissions goal of this project and resulted in the ISL G NZ architecture. Based on that architecture, the Cummins integration activities were evaluated to determine which were applicable to the Integration work plan for this demonstration project.

Given the demonstration vehicles were existing ISL G powered vehicles and the vehicle related changes were limited to the addition of a CCV system, larger catalyst and the associated plumbing and wiring, the most efficient method to carry out the demonstration vehicle "build" was to utilize a Cummins distributor rather than other options such as using the vehicle OEM production or prototype process. The integration work for this project was conducted by

Cummins Pacific, a Cummins distributor in southern California under the supervision of Cummins field engineering staff. Cummins Pacific has extensive experience with engine and aftertreatment repowers where custom fabrication of brackets, wiring and plumbing is key. They are also fully integrated with Cummins service and parts network and familiar with the demonstration fleets, further increasing the efficiency of this integration method.

Table 9 lists the major areas of integration work activities and identifies those which were required for this project and which were not required due to knowledge and experience gained from the design of the existing commercially available ISL G.

Table 9: Engine Vehicle Chassis Integration Design Activities

Engine Design Area	Changes relative to current ISL G	Integration Activities
Aftertreatment System	Larger TWC. Utilizing the ISX12 G TWC	Installation of larger TWC to ensure adequate fit with surrounding components, hoses, wire harness
Air Intake System	No changes	No activities planned
Charge Air Cooling	No changes	No activities planned
Compressed Air System	No changes	No activities planned
Cooling System	Addition of coolant loop to CCV filter assembly	Installation of coolant hoses. Adequate sizing of hoses for performance requirements.
Engine Mounting	No changes	No activities planned
Engine Braking	No changes	No activities planned
Front End Accessory Drive System	No changes	No activities planned
Fuel System	No changes	No activities planned
Lubrication System	Addition of CCV system	Installation of CCV filter, coolant, air and oil lines. Mounting height of CCV filter for adequate performance
Powertrain System	No changes	No activities planned
Engine Ratings (Power & Torque)	No changes	No integration activities planned, although vehicle performance will be evaluated.
Rear Gear / Flywheel Housing	No changes	No activities planned
Service Accessibility	Addition of CCV filter (scheduled maintenance item)	Adequate access for service
Starting System	No changes	No activities planned

Source: Cummins Westport, Inc.

Feasibility and Risk Analysis

Most of the vehicle integration specifications are inherently met given the demonstration vehicle already had a fully integrated ISL G engine and aftertreatment system.

An internal review of the above design strategy was performed covering the major vehicle design areas. As previously mentioned, this demonstration project utilized existing production vehicles powered by the current ISL G engine aftertreatment system. The changes planned for the ISL G NZ engine and aftertreatment have been identified and shown. For areas not impacted by the design changes in this project, Cummins existing IQA process was relied upon to minimize risk. Cummins has established IQA process to confirm Cummins Installation Requirements are met and to ensure the quality of the mechanic/electronic interfaces between Cummins Products and the related vehicle systems. The Cummins IQA process was a requirement for vehicles prior to production. For areas impacted by the ISL G NZ design changes, additional steps were taken to reduce the risk of the design strategy. Table 10 summarizes the design strategy risk analysis for vehicle integration.

Mechanical Components

The changes to the engine and aftertreatment system were not expected to change mounting to the vehicle chassis, compatibility with other powertrain components including transmission, driveline, axles, rear gear, flywheel housing components including PTOs, etc., or engine accessories including air conditioning or, fans. Therefore, specific integration activities were not required for these areas. One additional issue was the addition of the CCV system which includes an additional component to be mounted on the vehicle chassis and additional coolant and crankcase vapor hoses.

Fuel System

The vehicles used in this demonstration project were existing commercial products that had been in use with the demonstration fleets. The fuel storage system (CNG/LNG) specifications and installation were performed directly by the vehicle OEM or performed by a third party and approved by the vehicle OEM when the vehicle was first released for production. The installation of the ISL G NZ engine and aftertreatment was not impacting the vehicle fuel storage system or fuel delivery to the engine and therefore no specific actions in this area are required within this project.

Electrical System

The same approach was taken for the vehicle electrical system including the vehicle/engine communication protocols, on-board diagnostic requirements, etc. The vehicles and engines meet current requirements. The changes to the engine and aftertreatment did not impact these systems. Vehicle wire harness changes were required to accommodate the mid-bed catalyst oxygen sensor and CCV pressure sensor.

Exhaust Aftertreatment System

The catalyst used in production on the ISX12 G engine was used for this demonstration project. This TWC was approximately an inch longer and half an inch larger in diameter with the addition of a mid-catalyst temperature sensor. Although, excess space is typically not abundant on these vehicles in the area of the exhaust, specific installation requirements for the ISX12 G TWC have previously been established and were followed during the installation in these demonstration vehicles. Piping, mounting, and thermal protection were expected to be unchanged. As a reminder, the ISL G NZ engine three-way catalyst aftertreatment system is a passive system, packaged and mounted similarly to a vehicle muffler. This system does not use DEF fluid and therefore mounting concerns to protect against environment conditions (freezing) are not applicable. The mounting of the TWC followed existing Cummins AEB procedures to ensure proper installation design.

Table 10: Design Strategy Risk Analysis Summary

Engine / Vehicle Design Area	System / Components	Integration Strategy / Risk Mitigation
Mechanical Components	Aftertreatment System	Follow Cummins AEB: Automotive and Bus Installation Requirements – Natural Gas and LPG/Propane Catalyzed Exhaust Aftertreatment Systems
	Air Intake System	Derived from existing Cummins IQA approval
	Charge Air Cooling	Derived from existing Cummins IQA approval
	Compressed Air System	Derived from existing Cummins IQA approval
	Cooling System	Follow Cummins AEB: Remote Mount Crankcase Ventilation Filter (Breather) – Installation Requirements
	Engine Mounting	Derived from existing Cummins IQA approval
	Engine Braking	Derived from existing Cummins IQA approval
	Front End Accessory Drive System	Derived from existing Cummins IQA approval
	Fuel System	Derived from existing Cummins IQA approval
	Lubrication System	Follow Cummins AEB: Remote Mount Crankcase Ventilation Filter (Breather) – Installation Requirements
	Powertrain System	Derived from existing Cummins IQA approval
	Rear Gear / Flywheel Housing	Derived from existing Cummins IQA approval
	Service Accessibility	Installation conforming to Cummins AEBs for specific area. Utilized experienced Cummins Distributor (Cummins Pacific) for best practice and industry knowledge
	Starting System	Derived from existing Cummins IQA approval
Fuel Storage System	Fuel Storage (CNG)	Existing production vehicle, derive from vehicle OEM process

	Storage Capacity	Existing production vehicle, derive from vehicle OEM process
	Tank Installation	Existing production vehicle, derive from vehicle OEM process
Electrical System	Vehicle Communication Protocols	Existing production vehicle and engine which conform to HD vehicle communication protocols
	On-Board Diagnostics	Follow current model year EPA and CARB certification requirements for HD OBD requirements (Engine Manufacture Diagnostics - EMD+)
	Diagnostic Connector Locations	Existing production vehicle and engine which conform to HD vehicle diagnostic requirements
	Engine and Control System Power and Grounding	Existing production engine which conforms to Cummins Engineering Standard Work
	Electromagnetic Interference Compatibility	Existing production engine which conforms to Cummins Engineering Standard Work
	Wiring Interface Requirements	Existing production engine which conforms to Cummins Engineering Standard Work
	Electrical Component Installation	Existing production engine which conforms to Cummins Engineering Standard Work
	Fuel Level Display	Existing production vehicle, derive from vehicle OEM process
	Electronic Foot Pedal	Existing production vehicle, derive from vehicle OEM process
	Remote Throttle	Existing production vehicle, derive from vehicle OEM process
	Anti-lock Braking System & Traction Control Interface	Existing production vehicle, derive from vehicle OEM process
	Charging System	Existing production vehicle, derive from vehicle OEM process Existing production engine derive from Cummins AEB – Automotive/Bus Installation Requirements – Starting & Electrical Systems
	Exhaust Aftertreatment System Control and Diagnostics	Part of ISL G NZ design and EMD+ diagnostics requirements
Exhaust Aftertreatment	Sub-system requirements	Follow Cummins AEB: Automotive and Bus Installation Requirements – Natural Gas and LPG/Propane Catalyzed Exhaust Aftertreatment Systems

Source: Cummins Westport, Inc.

Detailed Design of Vehicle/Engine Integration

Two vehicles types, refuse collection vehicles and transit buses representing the principle customers for the current ISL G engine, were selected for integration and demonstration.

Product Validation Matrix

The product validation matrix discussed includes issues related to vehicle integration which can affect the engine and aftertreatment system design. CWI practice relies on the vehicle manufacturers to provide their own integration validation process.

Vehicle Integration Specifications

Vehicle integration is based on Cummins process and procedures for the proper integration of an engine into a vehicle chassis for the first time. A number of Cummins AEBs and the IQA developed for the existing ISL G engine were revised for proper installation ISL G NZ engine, including:

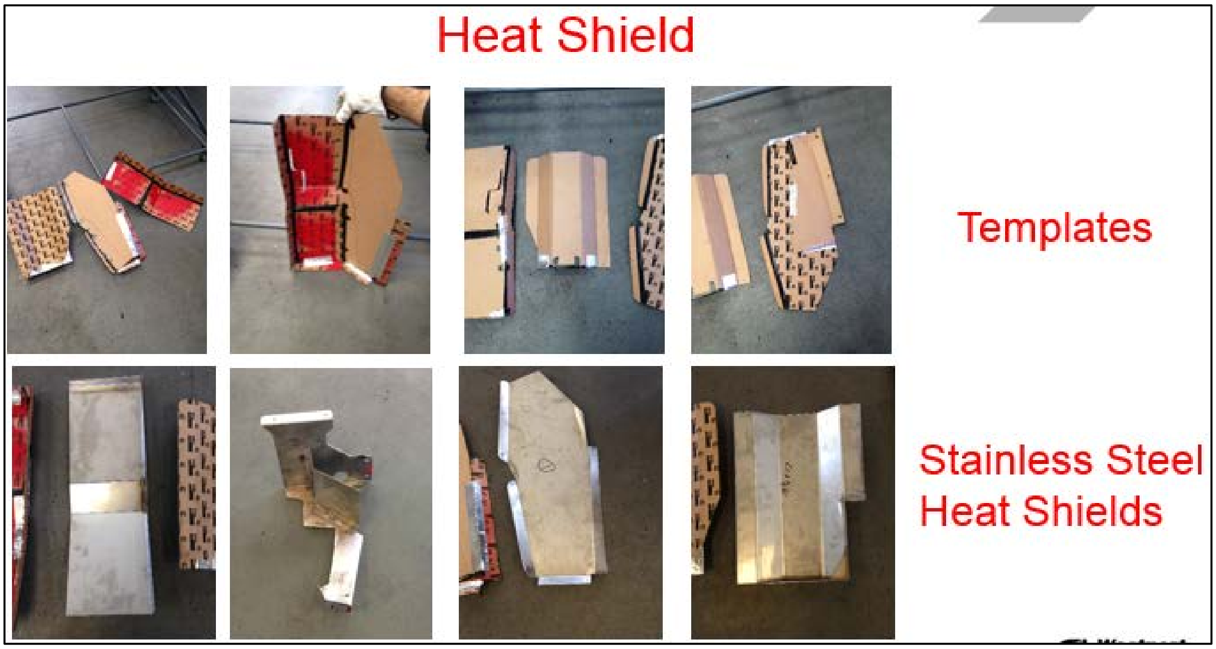
- 24.64 – CCV installation requirements,
- 21.20 – Natural gas aftertreatment,
- 21.100 – IQA worksheet,
- 15.78 - Electronic subsystem,
- 21.75 - ISL G Installation requirements,
- 21.164 - Electrical checklist

Customer engineering contacted bus manufacturers New Flyer, Gillig, DTNA, Novabus, Autocar, Peterbilt, Volvo, and Mack with new engine and aftertreatment cad models, AEBs, and IQAs for the new ISL G NZ engine. Gillig was given the installation photos of the first ISL G NZ San Diego bus. Installation of the ISL G NZ catalyst into the six Gillig 40' LF buses required modification to heat shielding, mounting straps, and exhaust pipes. Figures 21 and 22 show the modification work required to install the ISL G NZ components in the Gillig bus.

Figure 21: San Diego Transit 910 Installation Photographs

Source: Cummins Westport, Inc.

Figure 22: San Diego Transit 910 Exhaust/Catalyst Heat Shields



Source: Cummins Westport, Inc.

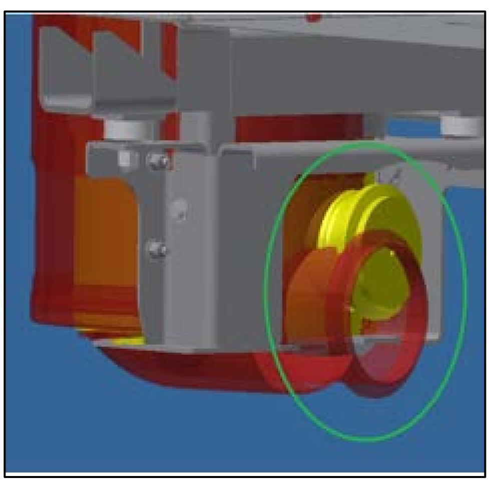
The Waste Management refuse truck installation shown in Figure 23 required less fabrication than the bus application. Autocar supplied the hardware for mounting the larger catalyst from their ISX G installation package. The exhaust pipe leading to the catalyst had to be modified for the larger catalyst inlet and the catalyst outlet pipe shortened to accommodate the added catalyst length. Figure 24 illustrates a slight offset in location of the catalyst requiring a new inlet pipe and Figure 25 shows the installed catalyst in the truck.

A vehicle mounting location for the CCV filter was required on the bus and truck. The addition of the crankcase pressure sensor had no impact on vehicle OEM integration since it is integral to the assembled engine.

Figure 23: WM-Oakland 265520 Installation

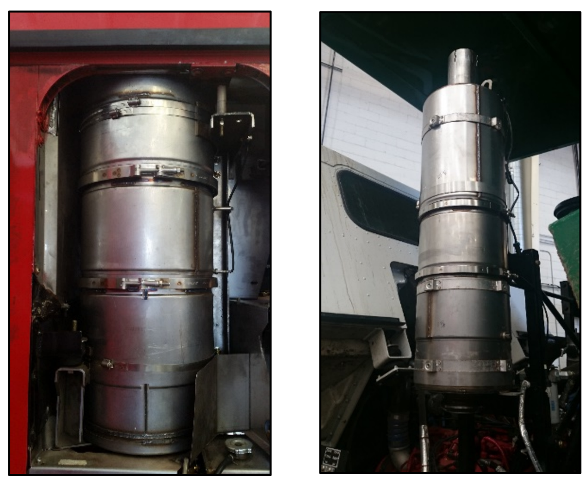
Source: Cummins Westport, Inc.

Figure 24: Location Difference Requiring New Inlet Pipe



Source: Cummins Westport, Inc.

Figure 25: TWC Installation on Trucks



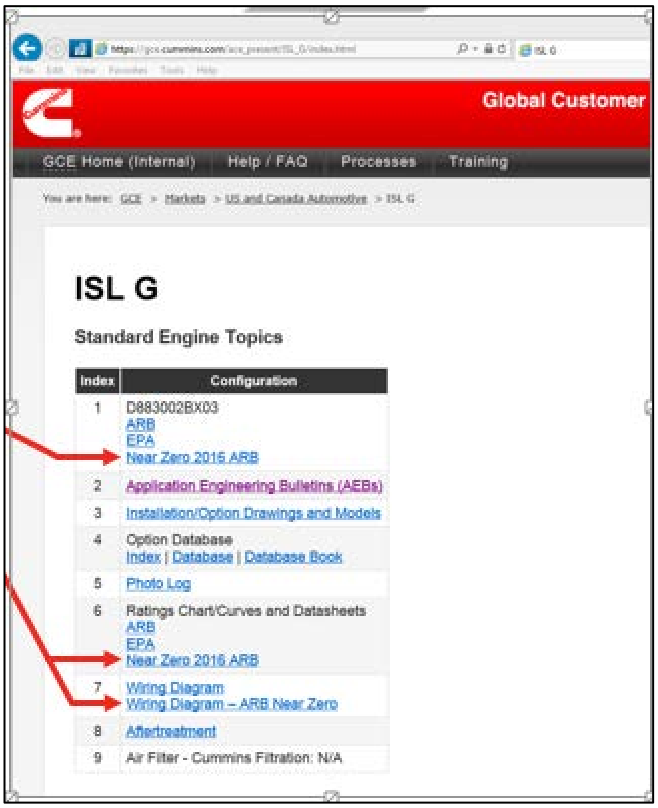
Source: Cummins Westport, Inc.

The Cummins Global Customer Engineering (GCE) website was updated with the ISL G NZ information on engine ratings, aftertreatment options, and OEM wiring harness information as shown in Figure 26. GCE is the primary source of technical information and literature for engine customers.

Identify and Evaluate Changes in Specifications.

The changes for the ISL G NZ are listed in Task 2.6.3. Changes in the exhaust configuration required to fit the aftertreatment system were minor and were not expected to have any effect of emissions or performance.

Figure 26: Cummins GCE Website



Source: Cummins Westport, Inc.

Build Production Intent Vehicles

A Rapid Truck engineering prototype vehicle was assembled with prototype hardware and driven on public roads in Indiana. This truck rapidly accumulated miles and running time on the engine and vehicle systems to identify any potential short-term drivability or vehicle-engine integration issues. The vehicle was testing the ISL G NZ engine from June, 2015. The vehicle was also used by the engineering teams for specific development activities.

Vehicle Integration Validation

The vehicle product validation plan was to demonstrate ISL G NZ engines and aftertreatment in a total of 13 customer vehicles including six transit busses and seven refuse trucks identified in Table 11. The field test duration was required to be at least six months.

Table 11: ISL G NZ Field Test Vehicles

Customer	Location	Application	ESN	Vehicle Unit Number	Installation Date
CR&R	Perris, CA	Refuse	73730860	57371	Feb 23, 2016
San Diego Transit	San Diego, CA	Transit	73753948	902	Sept 30, 2015
San Diego Transit	San Diego, CA	Transit	73753921	904	Oct 29, 2015
San Diego Transit	San Diego, CA	Transit	73757581	905	Oct 30, 2015
San Diego Transit	San Diego, CA	Transit	7375760	908	Nov 16, 2015
San Diego Transit	San Diego, CA	Transit	73758619	910	Aug 20, 2015
San Diego Transit	San Diego, CA	Transit	73761716	912	Dec 1, 2015
Waste Management	Santa Ana, CA	Refuse	73779339	212195	Aug 26, 2015
Waste Management	Santa Ana, CA	Refuse	73779053	212196	Sept 1, 2015
Waste Management	Santa Ana, CA	Refuse	73799810	212197	Sept 15, 2015
Waste Management	Oakland, CA	Refuse	7380715	265520	Aug 28, 2015
Waste Management	Oakland, CA	Refuse	73801114	265521	Sept 2, 2015
Waste Management	Oakland, CA	Refuse	73801169	265523	Sept 2, 2015

Source: Cummins Westport, Inc.

Establish Minimum Quantities for Validation

CWI internal engineering standards require using at least six field test vehicles testing the final production calibration for a period of at least eight consecutive weeks before the product can be used in production. For this field trial/demonstration 13 vehicles (seven refuse trucks and six transit buses) were included in the demonstration because the system configurations and engine control software may differ. At least one engineering vehicle was used for engineering tuning and accelerated durability tasks.

Conduct Chassis Dynamometer Cooling Test

A chassis dynamometer test was completed. The heat rejection of the ISL G NZ engine was the same as the current product ISL G engine. Any cooling system that is currently approved for use with an ISL G engine will be approved for ISL G NZ with no new testing required. This allows OEMs who currently use the ISL G engine to offer the ISL G NZ engine with no change to their cooling systems. There were no cooling system issues during the chassis dynamometer testing.

Independent Testing

CWI made an engine and aftertreatment system available for independent tests, although this was not requested by SCAQMD and therefore tests on the engine and aftertreatment were not conducted.

CHAPTER 4:
Vehicle Demonstration Plan

The plan was to demonstrate ISL G NZ engines and aftertreatment in 13 vehicles in total, six transit buses and seven refuse trucks, as summarized in Table 11. CR&R, San Diego Transit and Waste Management, provided the vehicles for the demonstration. Typical refuse vehicle and transit bus applications are shown in Figures 27 and 28.

Figure 27: Waste Management Unit 265520

Figure 28: San Diego Transit Unit 910

Source: Cummins Westport, Inc.

Vehicle Demonstration Plan

A Vehicle Deployment Plan was developed to outline the various aspects of the field test / demonstration activities.

Duration and Capability

The demonstration fleet consisted of 13 vehicles (six transit buses and seven refuse trucks). The performance of the vehicles was monitored with a data logger on each vehicle. The duration of the demonstration was planned to be at least six months.

Fleet Selection

The demonstration plan was for refuse trucks and transit bus customers to use the vehicles on the same routes as they did with the current product ISL G engines powered vehicle(s). The refuse trucks would drive the same routes and collect the same refuse as they did before the ISL G NZ installation. The transit customers would drive the same routes and transport the same riders as they did before the ISL G NZ installation. Waste Management (WM) and CR&R were chosen for refuse collection vehicles and San Diego Transit was chosen for transit bus application. Both companies have operated vehicles equipped with the current ISL G engines and have established service routes, CNG fueling stations, trained drivers, and trained mechanics.

Fleet Operation

The demonstration vehicles were to continue accessing fuel at the same fueling stations the vehicles used before the ISL G NZ installation. All demonstration vehicles had continuous data loggers installed. The data logger collected data whenever the engine was in operation. All data was wirelessly transmitted to the Cummins engineering team daily. All demonstration vehicles were supported by the local Cummins distributor and by the Cummins engineering team assigned to the VPI program.

Deployment Strategy

Fleet Size

Although the requirement for this project was for a minimum of one vehicle, the ISL G NZ engine was installed and tested in 13 vehicles. The buses were 40-foot low floor Gillig transit buses from the San Diego Transit fleet. There were three Waste Management refuse trucks tested in Santa Ana and three in the Oakland area. A single vehicle with CR&R in Perris, California was used. All 13 vehicles used ISL G engines before they were converted to the ISL G NZ engine by installing the set of near zero components as described in Task 3.

One of the Waste Management refuse trucks was used for the chassis dyno emissions testing at UC Riverside discussed in the Chassis Dynamometer Testing section.

Appropriate Fleet

Waste Management, San Diego Transit and CR&R all agreed to provide the trucks, drivers, mechanics to support this project, and to operate these units in commercial service.

Transient Operation and Grades

The ISL G NZ engine has the same ratings available as the current ISL G. The ISL G NZ engine meets the same transient performance targets as the current ISL G engine. Acceleration rates and torque curves of the ISL G NZ engine and aftertreatment system is similar to the engine acceleration of the current product ISL G engine as shown in Figures 13a and 13b of this report. The vehicles were operated in normal service which will include transient operation on city streets and freeways as well as hill climbing.

Functionality of Aftertreatment System

The ISL G NZ aftertreatment in the field test units was a production aftertreatment that was currently being sold with the ISX12 G engine. The aftertreatment is a passive three-way catalyst. The catalyst was slightly larger than the current ISL G catalyst and required slight vehicle modification to properly install the aftertreatment. The HD-OBD system monitors the functionality of the aftertreatment system during operation.

Functionality of Electronic Controls

The electronic controls for the ISL G NZ engine was the same as the ISL G engine. A pressure sensor was added to the vehicle to monitor CCV performance and a mid-bed catalyst temperature sensor was added to monitor catalyst performance. All other sensors, actuators, and controls logic remain unchanged from the current ISL G engine. Functionality of electronic controls is monitored by the on-board diagnostic system.

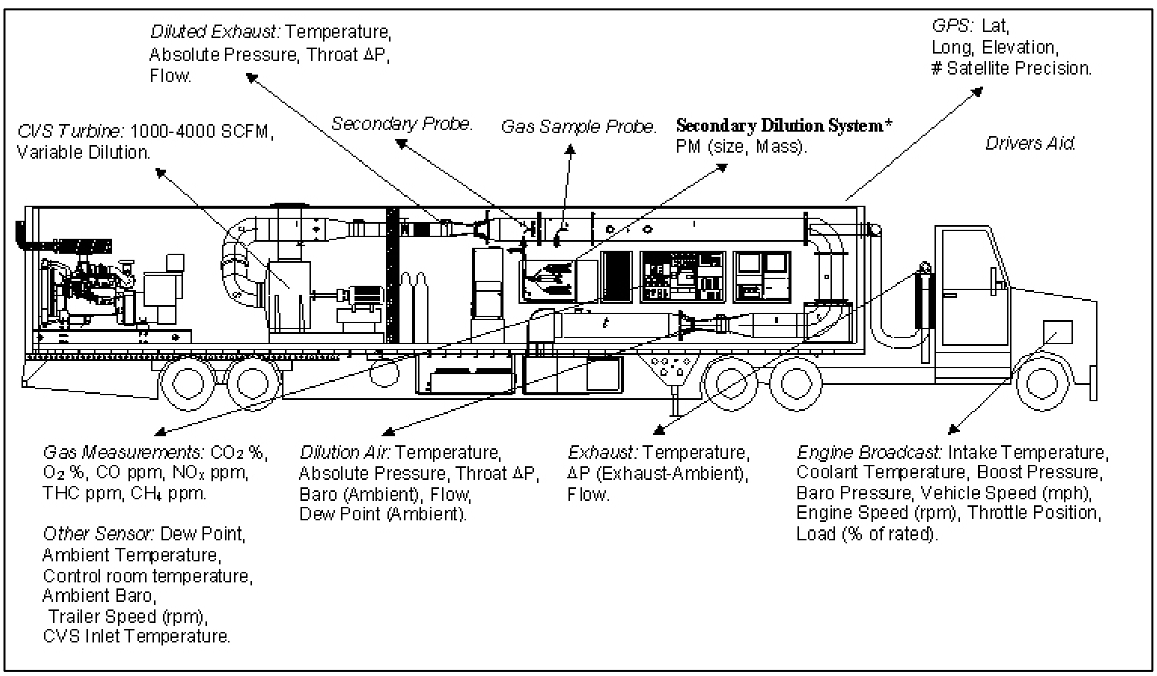
Optimization of Engine Calibration

The ISL G NZ engine was remotely monitored during the field tests. All fault codes generated an issue for that fault code and a team was assigned to investigate and resolve every fault code using the FIRG process. The software was largely identical to the software used on the current ISL G engine. It was expected that most diagnostic codes could be corrected by changes to engine calibration software.

Chassis Dynamometer Testing

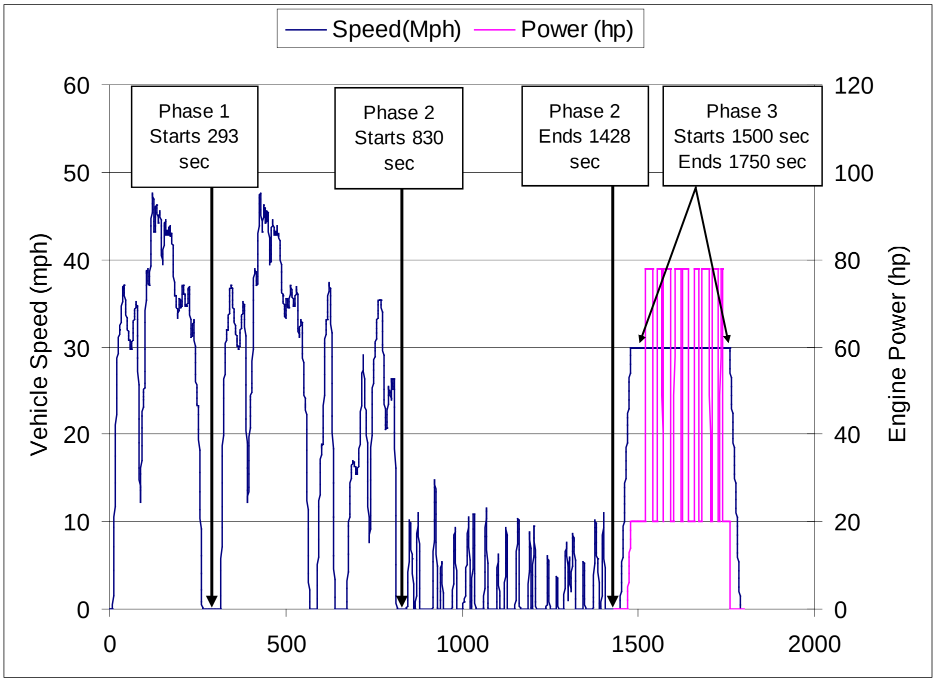
The chassis dyno emissions testing was conducted at the University of California, Riverside College of Engineering, Center for Environmental Research and Technology (CE-CERT) emission test facility. The facility is a recognized heavy duty emission testing laboratory and was approved by SCAQMD for this project. The emissions measurement equipment was contained in a mobile van (Figure 29). Emissions, performance, and fuel economy data was collected on the AQMD refuse truck cycle (Figure 30), Urban Dynamometer Driving Schedule, and Central Business District cycle.

Figure 29: University of California Riverside Emissions Measurement Trailer



Source: Cummins Westport, Inc.

Figure 30: AQMD Refuse Truck Cycle (AQMD-RTC)



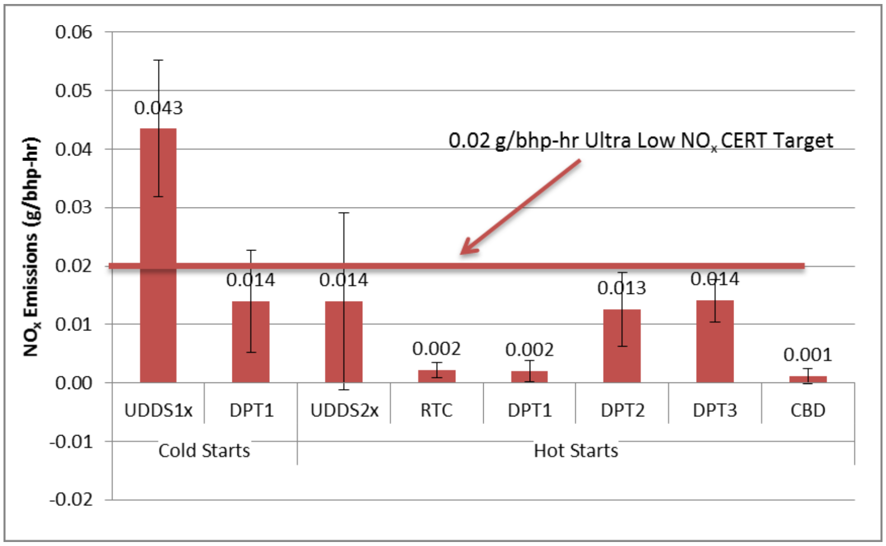
Source: Cummins Westport, Inc.

Testing was conducted in November 2015 and the final report, issued in February 2016, is included in Appendix A. The general conclusion of the report was that "*The ILS G NZ* [sic] *8.9 liter NG engine met and exceeded the target NOx emissions of 0.02 g/bhp-hr and maintained those emissions during a full ration of duty cycles found in the South Coast Air Basin.*" Figure 31 shows vehicle No 212195 undergoing emission tests. The UC Riverside testing showed "*ILS G NZ* [sic] *8.9 liter NG engine showed a NOx emissions below the proposed 0.02 g/bhp-hr emission target and average between 0.014 and 0.002 g/bhp-hr for the various hot start tests*", as shown in Figure 32.

Figure 31: Chassis Dynamometer Test Setup of Truck with ISL G NZ Engine

Source: Cummins Westport, Inc.

Figure 32: ISL G NZ Emissions Results From Chassis Dynamometer Tests



Source: Cummins Westport, Inc.

Data Collection Plan

The ISL G NZ demonstration fleet had data loggers installed on every vehicle. After initial installment, there were a few data loggers which had transmitting issues and required the Cummins data logger group to investigate and remedy. The data was sent wirelessly to Cummins daily. Data collected included engine speed and load, fuel usage, air flow, spark timing and EGR rates, coolant temperatures, miles driven and any fault codes from the diagnostic system.

Evaluate Vehicle Performance

The comparison of the ISL G NZ engine to the current product ISL G engine was aided by the fact that the ISL G NZ engine is operating in fleets with ISL G engines. The ISL G NZ engine required the changing of the CCV filter after every 2,000 hours of operation. All other maintenance schedules and procedures are the same as the current ISL G engine. The performance, fuel economy, and reliability of the field test vehicles was monitored throughout the field test.

Execute Demonstration Plan

Status of Demonstration Vehicles

The field test/vehicle demonstration was completed successfully, accumulating more than 564,000 miles. The demonstration duration, and project contract, was extended to the end of May 2017 to gather additional mileage. Some vehicles were decommissioned as per the originally planned demonstration end date due to fleets planned operation for these assets.

Table 12 shows the total accumulated miles of the field test vehicles as reported by the on-board data loggers.

Table 12: Field Test Fleet Data Logger Mileage Summary

Customer	ESN	Unit Number	Installation Date	Starting Miles	Starting Hours	Last Update*	Logger Time	Logger Distance	Last Miles	Last Hours	Total Hours	Total Test Miles
CR&R	73730860	57371	23-Feb-16	21122	1991.4	04-Apr-17	16922198	78417.844	48737	4701	2,709	27,615
SDT	73753948	902	30-Sep-15	37708	3136.45	6-Jun-17	32382673	176747.688	109849	8995	5,859	72,141
SDT	73753921	904	29-Oct-15	42834.1	3526.35	7-Feb-17	29341292	160176.188	99550	8150	4,624	56,716
SDT	73757581	905	30-Oct-15	46674		1-Jun-17	33507851	185895.063	115535	9308	9,308	68,861
SDT	73757560	908	16-Nov-15	45280	3715	6-Jun-17	34593341	190201.82	118211	9609	5,894	72,932
SDT	73758619	910	20-Aug-15	26986.9	2222.55	19-Jan-17	26084964	143084.625	88928	7246	5,023	61,941
SDT	73761716	912	01-Dec-15	43900		4-Apr-17	30983316	172574.461	107256	8606	8,606	63,356
WM-Santa Ana	73779339	212195	26-Aug-15	3194.1	423.12	6-Jun-17	21112981	62198.406	38657	5865	5,442	39,847
WM-Santa Ana	73779053	212196	01-Sep-15	5625.2	711.58	6-Jun-17	22469571	78728.016	48930	6242	5,530	43,305
WM-Santa Ana	73799810	212197	15-Sep-15	143.8	15.45	31-Oct-16	11086631	32260.797	20050	3080	3,064	19,906
WM-Oakland	73800715	265520	28-Aug-15	2957.5	152.13	7-Nov-16	8348415	19711.18	19642	2319	2,167	16,685
WM-Oakland	73801114	265521	2-Sep-15	2854		12-Sep-16	5711661	23711.328	14737	1587	1,587	11,883
WM-Oakland	73801169	265523	2-Sep-15	4068		18-Nov-16	7169768	21217.711	13187	1992	1,992	9,119
						** Several units decomissioned prior to June 2017 update*					Total Hours 61,805	Total Miles 564,306

Source: Cummins Westport, Inc.

Collect and Analyze Operational Data

Vehicle data was collected by the fleets through their regular maintenance activities and by CWI through the on-board dataloggers which record specific information from the engine control units (ECU's). Fleets typically record the following operational data:

- Demonstration vehicle mileage (Table 12).
- San Diego Transit vehicle fuel consumption (Table 13).
- San Diego Transit vehicle scheduled engine oil changes (Table 14) and preventive maintenance.
- Daily fluid level checks (engine oil, engine coolant, hydraulic fluid). Daily checks on the field test vehicles were conducted in the same manner and using the same schedule as other vehicles in the fleet.
- Vehicle pre and post trip general inspection. Daily checks on the field test vehicles were unchanged from the other vehicles in the fleet.

Table 13: Fuel Economy Summary from San Diego Transit

Bus #	Begin 5/11/2015	End 8/3/2016	Miles Traveled	Fuel Consumed	MPG
902	20,026	70,195	50,169	14,642.80	3.42
904	22,801	76,780	53,979	15,644.90	3.45
905	22,512	77,471	54,959	16,215.30	3.39
908	20,981	75,392	54,411	15,755.80	3.45
910	17,867	70,180	52,313	15,128.50	3.46
912	20,236	73,668	53,432	13,939.80	3.83

Source: Cummins Westport, Inc.

Table 14: San Diego Transit Scheduled Maintenance

Oil Changes Completed 5/11/2015 Through 8/3/2016											
902		904		905		908		910		912	
Completed	**Mileage**	**Completed**	**Mileage**	**Completed**	**Mileage**	**Completed**	**Mileage**	**Completed**	**Mileage**	**Completed**	**Mileage**
6/30/2016	66,452	7/11/2016	73,219	6/30/2016	72,541	7/19/2016	73,216	7/7/2016	66,755	7/25/2016	72,876
4/15/2016	60,521	5/11/2016	67,043	5/1/2016	66,284	5/28/2016	67,095	5/19/2016	60,619	6/1/2016	66,687
3/1/2016	54,434	3/26/2016	60,962	3/22/2016	60,706	4/13/2016	61,135	4/3/2016	54,569	4/16/2016	60,485
1/14/2016	48,556	2/10/2016	54,816	2/4/2016	54,736	2/16/2016	54,882	2/17/2016	48,329	2/24/2016	54,144
11/20/2015	42,426	12/17/2015	48,683	12/4/2015	48,369	12/21/2015	48,846	12/14/2015	42,212	1/5/2016	47,943
9/10/2015	36,357	10/19/2015	42,783	10/4/2015	42,510	10/23/2015	42,713	10/31/2015	36,125	11/9/2015	42,571
7/25/2015	30,276	8/26/2015	36,569	8/20/2015	36,449	9/9/2015	36,590	9/16/2015	30,121	9/9/2015	36,166
6/18/2015	24,431	7/7/2015	30,660	7/7/2015	30,482	7/18/2015	30,446	6/29/2015	24,058	7/27/2015	30,384
		5/26/2015	24,697	5/26/2015	24,441	6/9/2015	24,642	5/13/2015	18,152	6/12/2015	24,274

Source: Cummins Westport, Inc.

On-board dataloggers connected to the engine control units collected the following data:

- Accelerator pedal
- Active and inactive faults. Fault codes for the issues encountered during this project are shown in Table 15. The engine's data log is studied to aid with the resolution of fault code.
- Catalyst temperature
- Air flow temperature, pressure, and mass flow
- EGR flow temperature, pressure, and mass flow
- Gas flow temperature, pressure, and mass flow
- Battery voltage
- Coolant temperature
- Run time
- Estimated torque
- Engine speed
- Misfire
- Knock
- Motoring
- Oil pressure and temperature
- Vehicle speed

The field test performance was monitored through an internal Cummins development process referred to as FIRG (failure incident report group). All field test issues and test cell issues uncovered were captured and resolved using the FIRG process. A FIRG issues can originate from poor engine performance, a fault code, a part failure, or customer complaint. Figure 33 shows a snap shot of the FIRG issues at one point during this project.

Steps 1 – 4 cover the investigation into the potential issue. Once the potential issue is well defined and understood, then a root cause for the issue is identified in step 4. Steps 5-6 identify a solution and verify the effectiveness. Step 7 is implementing the solution.

All Class 3, 4, and 5 FIRG issues generated in this project having been resolved and closed. Table 15 shows all FIRG issues generated during this project. Overall, the engines performed very well during field tests.

Figure 33: Example of FIRG 9 Box During the ISL G NZ Project

Description	Investigate Step 0-4	Verify Step 5-6	Prevent Step 7	Low	Parts Lost	Open	Closed	Total	
Critical (Mission Disabling)	1	0	0	0	0	1	0	1	CLASS 5
Major (Warrantable)	3	1	0	0	0	4	2	6	CLASS 4
Minor (Non-warrantable)	0	1	0	0	0	1	2	3	CLASS 3
									CLASS 2
Total	4	2	0	0	0	6	4	10	CLASS 1

Source: Cummins Westport, Inc.

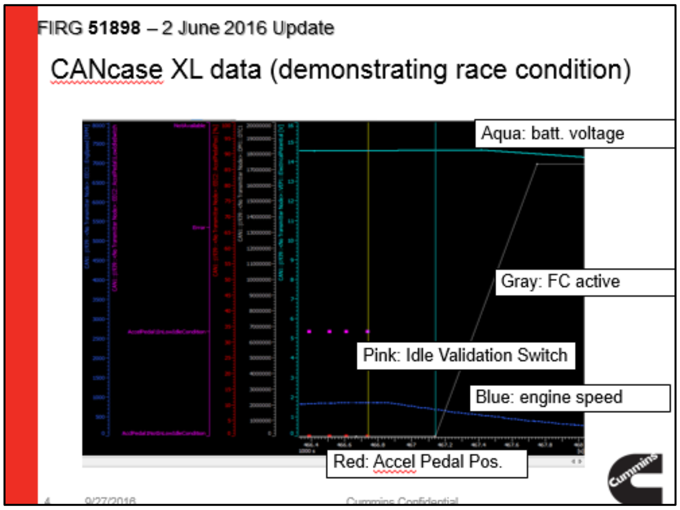
Table 15: FIRG Issue List

issue number	disablecode	warrantycode	team	issue title	issue creation date
50421	Y	Y	CPE	Cracked Piston : FC 1718 & 2457 - Engine Misfire	12-Nov-15
50236	N	Y	CUSTOMER ENGINEERING	FC 1117	30-Oct-15
51914	N	Y	CPE	multiple knock faults, cyl 3, 5, 6	30-Jan-16
52966	N	Y	MECHANICAL	Turbocharger compressor cover leak	28-Mar-16
53251	N	Y	MECHANICAL	impactor o-ring oil leak	30-May-16
51916	N	N	CPE	FC 1654 - misfire cyl 1	17-Feb-16
52459	N	N	CPE	FC2961 - EGR temp high	7-Apr-16
52577	N	N	CONTROLS	fc 1718 - misfire all cylinders	18-Apr-16
52769	N	N	CONTROLS	FC3436/6396 - CIL sensor above normal/erratic	27-Apr-16
52965	N	N	CPE	FC2725 - low fuel pressure	11-May-16
53253	N	N	CONTROLS	FC 2988 - high MAF	29-May-16
53250	N	N	CONTROLS	FC 141 - oil pressure OORL	7-Jun-16
53448	N	N	CPE	FC 1965 and 1966 - high catalyst temp	18-Jun-16
54077	N	N	CONTROLS	FC 1718 - misfire all cylinders	1-Aug-16
54669	N	N	MECHANICAL	loose vibration damper capscrews	24-Aug-16
49051	N	N	CPE	Cold Start Slow & Misfire	30-Jul-15
49150	N	Y	CPE	FC 2725 Fuel Inlet Pressure Below Normal Operating Range	6-Aug-15
49336	N	N	CPE	FC 5111	20-Aug-15
49427	N	Y	MECHANICAL	Clogged CCV Filter - Emulsion	27-Aug-15
50090	N	N	MECHANICAL	Oil Leak from the Impactor Breather	22-Oct-15
50213	N	Y	CPE	FC 5111	29-Oct-15
50423	N	Y	MECHANICAL	Impactor Breather Failed During Misfire Fault Codes	12-Nov-15
51931	N	Y	CONTROLS	FC 1718, 1864, 2686, and 6396 (misfire and O2 sensor)	1-Feb-16
51915	N	Y	CONTROLS	FC 731 - Cams and Crank Misalign	18-Feb-16
51899	N	Y	MECHANICAL	FC 555 - crankcase pressure high	21-Feb-16
51898	N	Y	CONTROLS	FC 3326/3528 TPS faults on multiplex	29-Feb-16
52458	N	N	CPE	FC1666 - Midbrick Temp Sensor Shorted	6-Apr-16
52457	N	N	CONTROLS	fc 2988 - high maf	6-Apr-16
52768	N	N	CONTROLS	FC2723 - FOP low	3-May-16
53767	N	N	CONTROLS	FC 6396 / 3436 - CIL O2 sensor data erratic/valid but high	6-Jun-16
53249	N	N	CONTROLS	FC 466 - WCV oor low	7-Jun-16
50422	N	Y	CONTROLS	Engine Surged & FCV Replaced	12-Nov-15
50510	N	N	SERVICE	FC 2377	19-Nov-15
52578	N	N	SERVICE	FC195/197 - failed/low coolant	16-Apr-16

Source: Cummins Westport, Inc.

The on-board dataloggers were critical to understanding any issues the field test engines experienced. An example of an issue uncovered and the data pulled from the vehicle data logger is FIRG issue 51898, titled “FC 3326/3528 TPS (throttle position sensor) faults on multiplex”. The engineer examined data logger data for: accelerator pedal, engine speed, battery voltage, and active fault, shown in Figure 34.

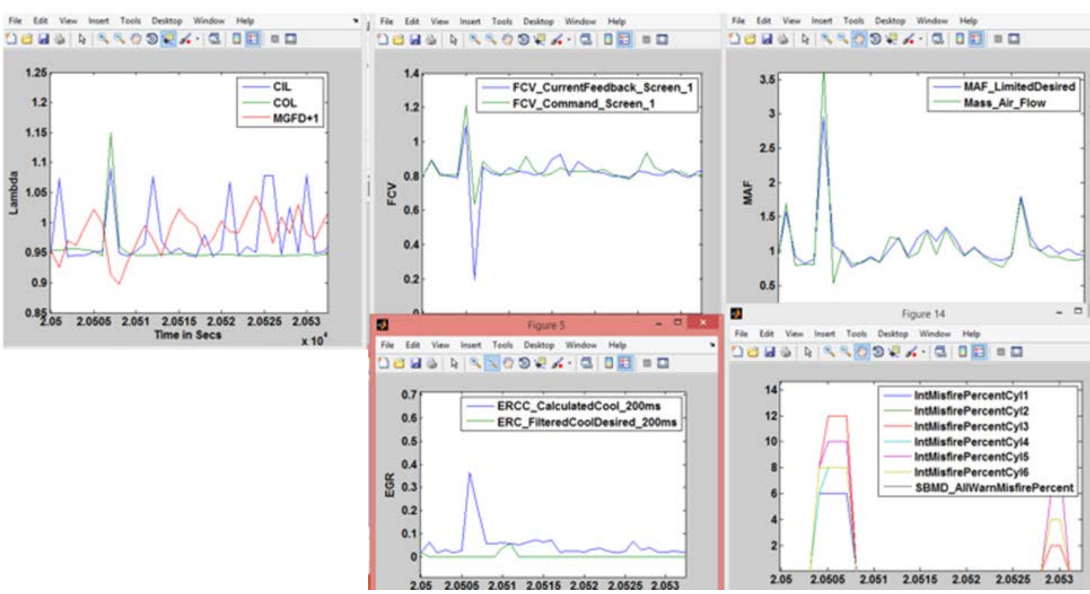
Figure 34: Sample Data Used to Investigate FIRG Issue 51898

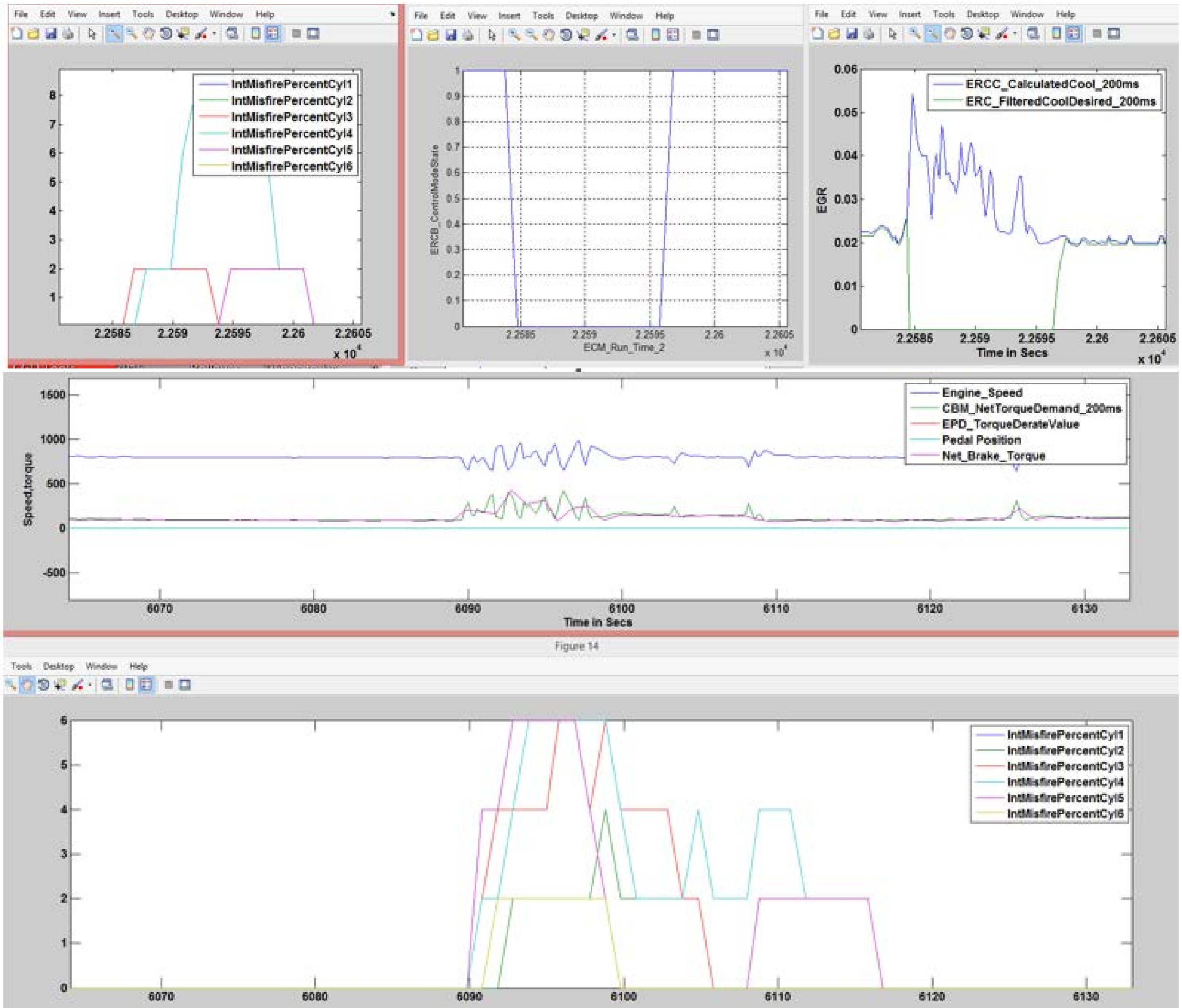


Source: Cummins Westport, Inc.

Another example is FIRG issue 52577 titled “FC1718 – misfire all cylinders”. The engineer used gas flow, air flow, EGR flow, misfire, engine speed, lambda, and torque to investigate the root cause. Sample data for these variables are shown in Figure 35.

Figure 35: Sample Data Used to Investigate FIRG Issue 52577





Source: Cummins Westport, Inc.

Independent Emission and Performance Testing

A demonstration vehicle was made available for independent tests if requested by SCAQMD but no requests were made and therefore no independent emissions and performance testing was conducted (outside of the chassis dyno testing performed and discussed in Task 4.1.2.7).

CHAPTER 5: Technology Transfer Activities

Technology Plan & Activities

CWI planned to make available, and has made available, to the public the knowledge gained in this project and promote the technical and economic benefits of this project through several ways and activities:

Commercial Product

The technology developed in this project was used to make available a commercial product, the ISL G Near Zero engine, which was launched in 2016. The ISL G NZ was made available to the public through the existing vehicle OEM channel. It is expected vehicles currently offering the ISL G as a power plant choice will offer the improved ISL G NZ emissions engine system and therefore cover the same market segment including medium- heavy-duty tractor, refuse truck, urban bus, school bus and other vocational applications. Cummins customer engineering worked with the vehicle OEMs such as New Flyer, Gillig, DTNA, Novabus, Autocar, Peterbilt, Volvo, and Mack, to convey technical specifications and information for integrating the new ISL G NZ engine into their vehicles and allow the vehicle OEMs to carry out their integration programs and offer the end vehicle to commercial availability. CWI has also issued press releases informing the general public and fleet buyers of the pending launch of the ISL G NZ engine.

Emissions Results

Once the near zero technology on the ISL G achieved emission certification requirements, emissions certification tests results and applications for certification were submitted to CARB and EPA. Official certification from both of these agencies were received late in 2015 including the first internal combustion engine to be certified to CARB Optional Low NOx 0.02g standard. Both of these agencies issue public documents indicating achievement of the emissions standards. CARB Executive Order for the engine show the numerical values of each emissions constituent.

CWI Natural Gas White Paper

CWI was planning to write a white paper on the technical aspects of natural gas engines and vehicles with a focus on emissions and include the Near Zero NOx technology gained in this project, but this project was not carried through to completion and no white paper was issued.

CWI Presentations

CWI regularly attends and presents at various technology forums and industry tradeshows and events. CWI planned to include the details of the technology developed during this project as well as the key results. These presentations included PowerPoint with results conveyed in various pictures, charts, graphs and tables.

Table 16 lists several of the events where CWI presentations occurred.

Table 16: CWI Presentation Events

Event	Approximate Date
NGVA (Natural Gas Vehicle Association) Conference and Expo	September 2015
NGVTF (Natural Gas Technology Forum)	October 2015
CWRE (Canadian Waste and Recycling Expo)	November 2015
CTA (California Transit Association) Fall Conference	November 2015
Cummins Bus Council Meetings	Fall 2015 / Spring 2016
GNA Game Changer	February 2016
ACT Expo (Alternative Clean Transportation Expo)	May 2016
CleanTech OC “Drive Mobility 3”	June 2016
Wastecon Expo	August 2016
NGVA (Natural Gas Vehicle Association) Conference and Expo	September 2016

Source: Cummins Westport, Inc.

CWI was involved in a major industry event hosted by Gladstein Neandross & Associates (GNA) titled “Game Changer NGV Industry Summit” on February 24, 2016 in Long Beach California. GNA released their white paper which “explores the need – and leading approaches – to immediately start deploying zero-emissions and near-zero-emissions heavy-duty vehicle (HDV) technologies on a wide-scale basis in the US” (http://ngvgamechanger.com/). In addition to the release of the GNA white paper, there were numerous presentations including air quality issues, the technical solutions, and deployment scenarios. Rob Neitzke, CWI President, presented the “ISL G Near Zero” product which explained the technology, emissions benefits and the availability/commercialization plans.

CWI presented the ISL G Near Zero Technology at the Advanced Clean Transportation (ACT) Expo in Long Beach California, which is the premier alternative fuel vehicle event in North America.

Cummins Pacific representatives presented at Clean Tech OC’s “Driving Mobility 3” event in Irvine, California on June 29th, 2016. CleanTech OC is a trade association that promotes economic growth in the Orange Country clean technology industry. The focus of this presentation was the use of ISL G NZ with renewable natural gas (RNG). CWI displayed an ISL G NZ engine at the Wastecon Expo in Indianapolis Indiana on August 22, 2016, where the focus was on the refuse segment. CWI presented the Near Zero technology at NGVA’s annual meeting and industry summit, September 7-9, 2016 in Denver, Colorado.

OEM Product Information Sessions

New technology and product presentations were created for the Cummins OEM account teams. These teams interface directly with each of the vehicle OEMs (Peterbilt, Kenworth, DTNA, New Flyer, Autocar, Gillig, etc.). Additional presentations were created for the OEMs to use internally within their company and also with their customers – the end user of the vehicle and engine system.

Maintenance Training

Training on CWI engines was provided to service providers through the Cummins dealer network. Information was updated to include the ISL G NZ engine.

CWI Website Information

CWI's public website (cumminswetport.com) hosts a section "Natural Gas Academy" where technology and industry information is available. This includes written information on natural gas and vehicle systems, videos on natural gas and CWI engine walk-around where the engine is presented at a high level. Updates to this website were made to include the ISL G NZ engine and aftertreatment.

Intended Use for and Users of the Project Results

The results of this project, as presented in the final report and disseminated through technology transfer activities, could be used by the following users for these respective intended uses:

Government emission regulators will be able to use the final project report to confirm natural gas internal combustion engines in heavy-duty automotive applications are capable of reaching "near zero" NOx and PM emissions. This will provide valuable insight into current technology as well as the potential capability of future technology and technology costs. With that data, regulators can make better informed decisions for the content and timing of state and federal emission regulations.

Air quality policy makers will also be able to use the information in the final report to confirm NG engine technology is a viable option to reach near zero emissions levels. Confirmation of this technology's capability allows policy makers to substantiate air quality improvement roadmaps with higher confidence both from a technical capability standpoint but also from a cost standpoint as they have a more accurate view of the vehicle and infrastructure implementation requirements. This same view is not as clear with future technologies that haven't been proven technically or ones that are not currently widely integrated by vehicle manufactures.

Although CWI is already well engaged with all major vehicle OEMs in the heavy-duty market and has regularly been sharing product information, the information in the final report will provide additional information on the process CWI used to achieve these results. For those OEMs not familiar with CWI products, they will be exposed to the engine and aftertreatment technology architecture used to achieve near zero emissions and the durability testing conducted on real world vehicles.

Engine manufactures will use the final report results to gain understanding for the engine and aftertreatment architecture used to achieve near zero emissions. This may alter their research and development plans to help them achieve lower emissions, possibly impacting their technology architecture decisions and/or changing their planned completion dates. It could spur competitors to accelerate commercial plans for near zero engines. It will also provide a clear picture of CWI's chosen near-term architecture which will indicate midterm and possibly long-term technology direction.

For heavy-duty fleets that are evaluating new engine technology, the information in the final report will provide them with a technical assessment of the complexity and emission performance of CWI's Near Zero technology. These fleets are faced with significant investment costs in vehicle and infrastructure capital purchases as well as personnel training for future low emissions technology. This report will aid with their evaluation of low emissions technology. The report will also provide a better understanding for the expected range of heavy-duty vehicle availability for the new ultra-low emissions engine and the applications which make use of this engine.

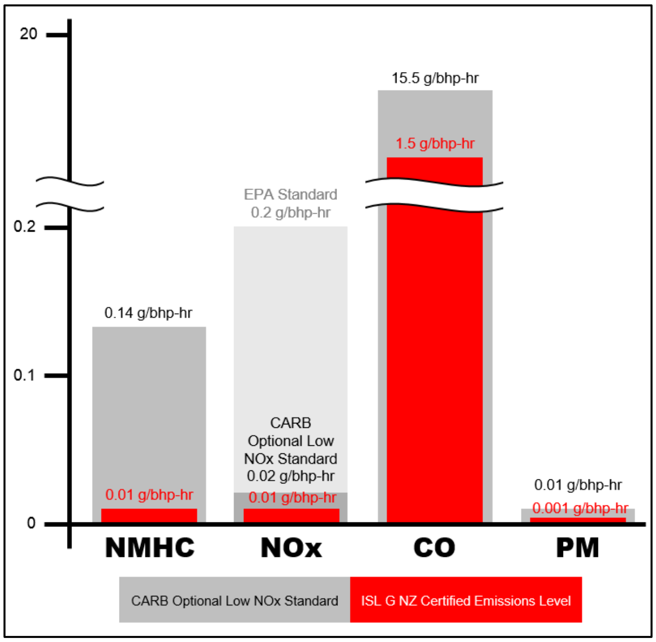
CHAPTER 6: Project Results, Conclusions and Recommendations

Project Results

Each of the project objects were successfully achieved. The key project objectives and results were as follows:

- *Design, develop and demonstrate an ultra-low emissions, commercially viable natural gas engine suitable for on-road heavy duty vehicle applications.*
    - o The ultra-low emission engine, called the ISL G NZ, was developed and demonstrated in 13 vehicles (six transit buses and seven refuse trucks) which were demonstrated in commercial operation accumulating a total of 564,306 miles and 61,805 hours.
    - o Demonstrated a peak rating of 320 hp and 100 ft per lb of torque
- *Achieving emissions targets of 0.02 g/bhp·hr NOx, 0.01 g/bhp·hr PM, 0.14 g/bhp hr NMHC, and 15.5 g/bhp·hr CO or lower as determined by the heavy duty engine FTP.*
    - o The ISL G NZ received Heavy Duty engine certification from CARB and EPA with FTP test certification values of 0.01 g/bhp·hr NOx, 0.001 g/bhp·hr PM, 0.01 g/bhp hr NMHC, and 1.5 g/bhp·hr CO (Figure 36).

Figure 36: Emission Results



Source: Cummins Westport, Inc.

- *Keeping exhaust NH_3 emissions as low as achievable while targeting NH_3 emissions at 10 ppm or lower,*
    - Although the NH_3 emissions stretch target of 10 ppm was not met, the internal NH_3 emissions goals were met with NH_3 emissions of less than 87 ppm measured in the CHET cycle.
- *Being thermally and fuel efficient, incorporating methods to achieve minimal, or zero, fuel economy penalties relative to 2010 EPA and ARB certified diesel engines in similar duty cycle, and*
    - Demonstrated transit fuel economy of 3.39 to 3.83 mpdge. UC Riverside's third party testing indicated 4.5 mpdge for the regional port cycle (DPT3) to 2.5 mpdge for CBD cycle.
- *Being certified by the US.EPA and CARB.*
    - Received CARB and EPA heavy-duty engine emissions certification in November 2015

Conclusions

Based on the results of this project and the data presented in this report, the project team's primary conclusion is that using SESI technology with the addition of closed crankcase ventilation system, an improved three-way catalyst and optimized engine controls, a natural gas engine suitable for on-road heavy-duty applications can achieve ultra-low emissions in a commercially viable manner, specifically:

- Achieve emissions targets capable of being certified to EPA and CARB standards of 0.02 g/bhp·hr NOx, 0.01 g/bhp·hr PM, 0.14 g/bhp hr NMHC, and 15.5 g/bhp·hr CO as determined by the heavy duty engine FTP,
- Keep ammonia levels low (87 ppm demonstrated), and
- Be thermally and fuel efficient.

Recommendations

CWI recommends proceeding with commercialization of the ISL G Near Zero engine and aftertreatment, which will include the following activities:

- Technical – validate the technical attributes of the engine, ensuring the performance (i.e. power and torque), reliability, and durability targets are met.
- Purchasing – establishes the suppliers and supplier agreements for the various engine components.
- Manufacturing – complete manufacturing activities at the Cummins engine plant in Rocky Mount, North Carolina which address the additions/differences in assembly and

testing of the ISL G Near Zero engines from the current ISL G engines before being shipped to the vehicle OEM.

- Customer engineering – work with the vehicle OEMs to ensure the vehicle OEM understands the engine and aftertreatment integration requirements for mounting in the vehicle chassis and address any OEM requests or issues related to the new engine.
- Marketing – convey the product message to the vehicle OEMs including typical marketing communication, sales training and ordering process. Also address public communication, directed towards end users and other stakeholders.
- Customer care – ensure the service and parts network is ready to support the engine post launch including ensuring readiness at the Cummins Distributors.
- Finance – ensure the commercial development program is adequately budgeted and post launch business impact is forecasted.

A new commercial development program was launched in early 2015 with the goal of releasing a 0.02g NOx certified ISL G engine system for production in 2016. While the last portions of this project were being carried out, the commercial development program was successfully completed and the project was launched in mid-2016.

The success of the near zero technology and application to the ISL G resulting in the commercial release of the ISL G Near Zero, opens up the opportunity to apply this technology to other engine platforms such as the ISX12 G and ISB6.7 G bringing those engines to a near zero NOx emissions level. CWI recommends these ultra-low emission commercial opportunities be pursued.

Benefits to California

This project has successfully completed the engine technology and demonstration program to achieve ultra-low emissions targets including 0.02g/bhp hr NOx level. One of the largest sources of NOx emissions in the South Coast Air Basin is attributed to heavy-duty on-road vehicle emissions. Even with replacement of the older vehicles with new vehicles meeting current EPA and CARB standards, the NOx emissions from this source category are still projected to be one of the largest contributors. The availability of an ultra-low emission heavy-duty natural gas engine, with NOx reduction of over 90% from the current federal standard would lead to significant air quality improvements as the market adopts this technology and vehicles are replaced. The emissions of ten (10) ISL G Near Zero powered bus would be the equivalent of one bus powered by a 2010 EPA certified engine.

In addition to the air quality emissions, this engine when combined with renewable natural gas (RNG) can achieve significantly greater GHG emissions reductions and in some instances offer a "near zero" GHG emissions profile.

Various industry stakeholders, including consultants, government agencies, and OEMs, are projecting significant natural gas vehicle penetration in the North American heavy-duty commercial vehicle market. The technical achievements in this project further support California and regional regulatory policy for lower emissions technology by proving natural gas heavy-duty engines are able to achieve ultra-low emissions and offer a highly cost effective emissions reduction solution in comparison with other zero and near-zero emission driveline systems and technologies currently used or anticipated for heavy-duty commercial vehicle applications. It further substantiates the ability to rapidly implement cleaner solutions through incentive funding or public fleet mandates or both.

ACROYNMS AND ABBREVIATIONS

Acronym	Definition
CAD	Computer aided design
CCC	Closed coupled catalyst
CHET	Cold/hot emission test
CNG	Compressed natural gas
CO	Carbon monoxide
CCV system	Closed crankcase ventilation system
CWI	Cummins Westport Inc.
EGR	Exhaust gas recirculation
EMP	Exhaust manifold pressure
GHG	Greenhouse gases
HC	Hydrocarbons
HEGO sensor	Heated exhaust gas oxygen sensor
ICM	Ignition control module
HD-OBD	Heavy duty onboard diagnostics
LNG	Liquefied natural gas
NH_3	Ammonia
NMHC	Non methane hydrocarbons
NOx	Oxides of nitrogen
OBD	Onboard diagnostics
OEM	Original equipment manufacturer
PM	Particulate matter
PFI	Port fuel injection
RNG	Renewable natural gas
SCR	Selective catalytic reduction
SESI	Stoichiometric, EGR, spark ignition
SI	Spark ignition
TWC	Three way catalyst
UEGO sensor	Universal exhaust gas oxygen sensor
ULSD	Ultra-low sulfur diesel
VGT	Variable geometry turbo

APPENDIX A: University of California Riverside Report

Final Report

Ultra-Low NO_x Natural Gas Vehicle Evaluation ISL G NZ

November 2016

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Disclaimer

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Abstract

Heavy duty on-road vehicles represent one of the largest sources of NO_x emissions and fuel consumption in North America. Heavy duty vehicles are predominantly diesels, with the recent interest in natural gas (NG) systems. As emissions and greenhouse gas regulations continue to tighten new opportunities for advanced fleet specific heavy duty vehicles are becoming available with improved fuel economy. NO_x emissions have dropped 90% for heavy duty vehicles with the recent 2010 certification limit. Additional NO_x reductions of another 90% are desired for the South Coast Air basin to meet its 2023 NOx inventory requirements.

Although the 2010 certification standards were designed to reduce NO_x emissions, the in-use NO_x emissions are actually much higher than certification standards. The main reason is a result of the poor performance of aftertreatment systems for diesel vehicles during low duty cycle operation. Recent studies by UCR suggest 99% of the operation within 10 miles of the ports represented by up to 1 g/bhp-hr. Thus, a real NO_x success will not only be providing a solution that is independent of duty cycle, but one that also reduces the emissions an additional 90% from the current 2010 standard.

The ISL G NZ 8.9 liter NG engine met and exceeded the target NOx emissions of 0.02 g/bhp-hr and maintained those emissions during a full ration of duty cycles found in the South Coast Air Basin. The other gaseous, particulate matter, particle number and selected non regulated emissions were similar to previous levels. It is expected NG vehicles could play a role in the reduction of the south coast NOx inventory problem given their near zero emission factors demonstrated.

Acronyms and Abbreviations

ARB ....Air Resources Board
bs...brake specific
CE-CERT..College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR..Code of Federal Regulations
CO..carbon monoxide
CO_2...carbon dioxide
CNG ....compressed natural gas
CWI..Cummins Westport Inc.
FID ....flame ionization detector
NH_3 ....ammonia
g/bhp-hr..grams per brake horsepower hour
lpm ....liters per minute
MEL ....mobile emission laboratory
NO_x ....nitrogen oxides
N_2O ....nitrous oxides
OEM...original equipment manufacturer
PM..particulate matter
$PM_{2.5}$ ....ultra-fine particulate matter less than 2.5 µm (certification gravimetric reference method)
PN ....particle number
PSD ....particle size distribution
RPM ....revolutions per minute
scfm..standard cubic feet per minute
THC..total hydrocarbons
UCR ....University of California at Riverside
FE..Fuel economy
GDE ....gallons diesel equivalent
NG..natural gas
LNG ....liquid natural gas

Executive Summary

Heavy duty on-road vehicles represent one of the largest sources of NO_x emissions and fuel consumption in North America. Heavy duty vehicles are predominantly diesels, with the recent penetration of natural gas (NG) engines in refuse collection, transit, and local delivery where vehicles are centrally garaged and fueled. As emissions and greenhouse gas regulations continue to tighten, new opportunities to use advanced fleet specific heavy duty vehicles with improved fuel economy are becoming available. NO_x emissions have dropped 90% for heavy duty vehicles with the recent 2010 certification limit. Additional NO_x reductions of another 90% are desired for the South Coast Air basin to meet its 2023 NO_x inventory requirements.

Although the 2010 certification standards were designed to reduce NO_x emissions, the in-use NO_x emissions are actually much higher than certification standards. The main reason is a result of the poor performance of aftertreatment systems for diesel vehicles during low duty cycle operation. Recent studies by UCR suggest 99% of the operation within 10 miles of the ports are up to 1 g/bhp-hr NO_x. Stoichiometric natural gas engines with three-way catalysts tend to have better low duty cycle NO_x emissions than diesel engines with SCR aftertreatment systems. Thus, a real NO_x success will not only be providing a solution that is independent of duty cycle, but one that also reduces the emissions an additional 90% from the current 2010 standard.

Goals: The goals of project are to evaluate the ISL G NZ (near zero) 8.9 liter ultra-low NO_x NG vehicle emissions, global warming potential, and fuel economy during in-use conditions. This report presents a summary of the results and conclusions of ultra-low NO_x NG vehicle evaluation.

Approach: The testing was performed on UC Riverside's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside CA just east of the South Coast Air Quality Management District (AQMD). The cycles selected for this study are representative of operation in the South Coast Air Basin and included the urban dynamometer driving schedule, the near dock, local, and regional port cycles, the AQMD refuse cycle, and the central business district cycle.

One of the difficulties in quantifying NO_x emissions at 90% of the 2010 certification level (~ 0.02 g/bhp-hr), is the measurement method is approaching its detection limit. Three upgraded NO_x measurement methods were considered which include a raw NO_x measurement integrated with real time exhaust flow, a real-time ambient correction approach, and a trace level ambient analyzer for accurate bag analysis. In summary the improved methods varied in their success where the raw sampling approach showed to be the most accurate and precise over the range of conditions tested.

In addition to the regulated emissions, the laboratory was equipped to measure particle size distribution, particle number, soot PM mass, ammonia, and nitrous oxide emissions to investigate any dis-benefit resulting from the ISL G NZ engine and aftertreatment system.

Results: The ISL G NZ 8.9 liter NG engine showed NO_x emissions below the proposed 0.02 g/bhp-hr emission target and averaged between 0.014 and 0.002 g/bhp-hr for the various hot start tests, see Figure ES-1. The NO_x emissions (g/bhp-hr) decreased as the duty cycle was decreased which was the opposite trend for the diesel vehicles (where emissions increased as duty cycle decreased). The large error bars (represented by 1 standard deviation) may suggest measurement variability, but when the real-time data was investigated, one can see the variability was a result of test-to-test differences from a few isolated NO_x events during rapid throttle tip-in at idle, see Figure ES-2. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle where more gradual accelerations are desired. This is also evident with the more gradual accelerations of the near dock and local port cycles which showed smaller error bars and lower average emission factors, see Figure ES-1.

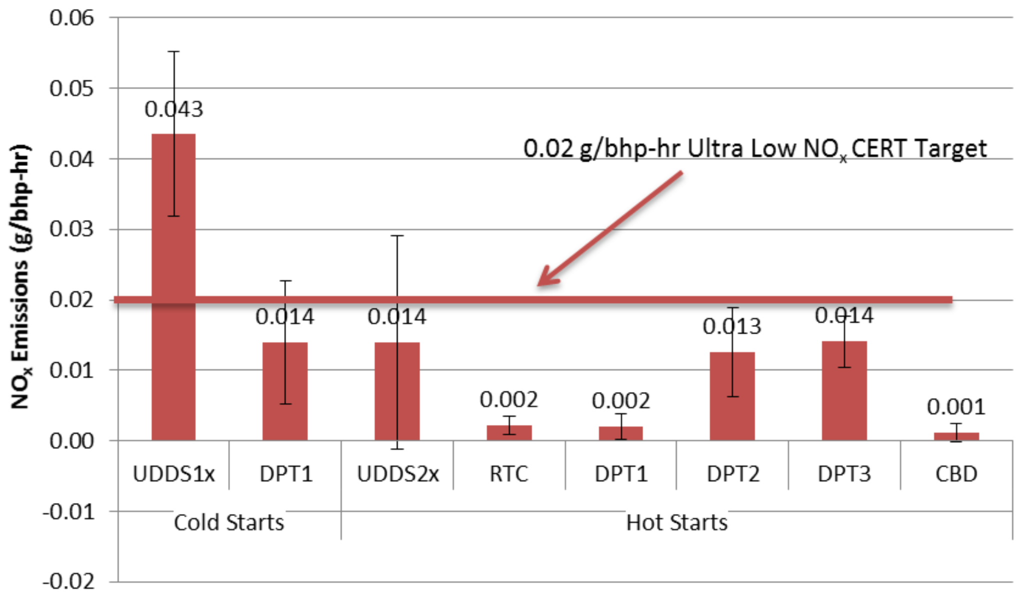


Figure ES-1 Cycle averaged NO_x emissions for the ISL G NZ 8.9 liter equipped vehicle

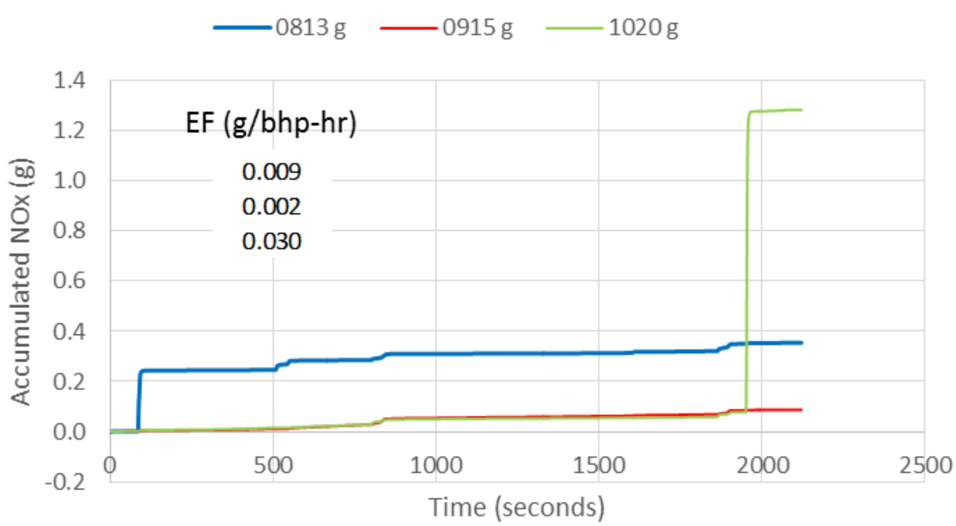


Figure ES-2 Real-time NO_x accumulated mass for the three UDDS hot cycles

[1] Individual accumulated and integrated EF for the UDDS cycle is shown in the figure above. The average of these tests is represented in Figure ES-1, UDDS cycle (0.14 g/bhp-hr).

Cold start emissions represented a significant part of the total NO_x emissions where 90% of the NO_x emissions occurred in the first 200 seconds of the cold UDDS test. Once the catalyst was warmed up, the remaining portions of the cold UDDS test showed low NO_x emissions similar to the hot UDDS test. The hot/cold UDDS weighted emission was 0.0181 g/bhp-hr (weighted as $1/7^{th}$ of the hot cycle) which is below the 0.02 g/bhp-hr standard. Once the TWC catalyst lights off, its NO_x reduction potential remains at a high performance unlike diesel SCR equipped engines where low duty cycles (associated with SCR temperatures below 250C) will cause the SCR performance to decline.

The other emission such as carbon monoxide, particulate matter, particle number, particle size distribution, nitrous oxide, and ammonia were similar to previous versions of the same stoichiometric 8.9 liter engine certified to 0.2 g/bhp-hr NO_x. For example PM was typically below 0.001 g/bhp-h (90% below the standard), ammonia was typically above 200 ppm. This suggests the reduced NO_x emissions did not come at the expense of an increase in other species. The methane emissions were notably lower than the 0.2 g/bhp-hr NOx version of the same engine. The lower methane emissions may be a result of the closed crankcase ventilation system. The fuel economy also appeared to be similar to previous versions of the same engine displacement where the UDDS showed the lowest CO_2 emissions and were below the current FTP standard of 555 g/bhp-hr for both the cold start and hot start tests during in-use chassis testing.

Summary: In general the ISL G NZ 8.9 liter engine hot/cold emissions were within the 0.02 g/bhp-hr certification standard for all the cycles tested. Ironically these emissions factors were maintained for the full range of hot-start duty cycles found in the South Coast Air Basin unlike other heavy duty diesel fueled technologies and certification standards. The other gaseous and PM emissions were similar to previous levels. It is expected NG vehicles with the ISL G NZ could play a role in the reduction of the south coast NO_x inventory in future years given the near zero emission factors demonstrated on each test cycle. Additional research is needed to see if the on-road behavior is similar to test cycles and if there are any deviations as the vehicles age.

1 Background

1.1 Introduction

Heavy duty on-road vehicles represent one of the largest sources of NO_x emissions and fuel consumption in North America. Heavy duty vehicles are predominantly diesels, although there is increasing interest in natural gas (NG) systems. As emissions and greenhouse gas regulations continue to tighten new opportunities for advanced fleet specific heavy duty vehicles are becoming available with improved fuel economy. At the same time NO_x emissions have dropped 90% for heavy duty vehicles with the recent 2010 certification limit. Additional NO_x reductions of another 90% are desired for the South Coast Air basin to meet its 2023 NO_x inventory requirements. Thus, an approach to reduce emissions also needs lower fuel consumption to the extent possible.

1.2 NO_x Emissions

Although the 2010 certification standards were designed to reduce NO_x emissions, the in-use NO_x emissions are actually much higher than certification standards for certain fleets. The magnitude is largely dependent on the duty cycle. Since engines are certified at moderate to high engine loads, low load duty cycle can show different emission rates. For diesel engines low load duty cycles have a significant impact in the NO_x emissions. The NO_x cold start emissions for the first 100 seconds were over 2.2 g/hp-h where for the same time frame with the hot cycle it was 0.006 g/hp-h [1], see Figure 1-1. The cold start emissions were ten times higher than the certification standard and much higher than the corresponding hot start emissions. Additionally the stabilized emission of the two systems over the same time period was very similar at 0.05 g/hp-h (about 75% below the standard). The main cause for the high NO_x emissions is low selective catalytic reduction (SCR) inlet temperatures resulting from low power operation.

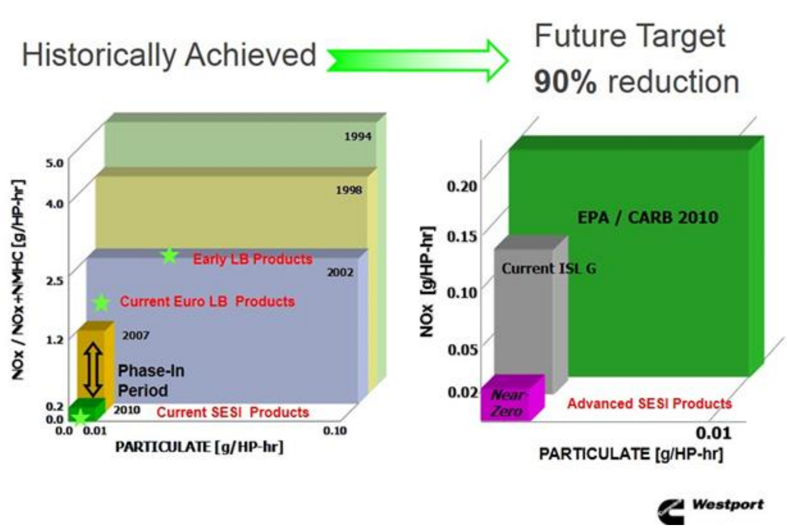


Figure 1-1 Engine dynamometer NO_x and PM certification emissions standards (source CWI)

[1] Wayne Miller, Kent C. Johnson, Thomas Durbin, and Ms. Poornima Dixit 2013, In-Use Emissions Testing and Demonstration of Retrofit Technology, Final Report Contract #11612 to SCAQMD September 2013.

These same trucks were tested on cycles designed to simulate port activity[2]. The port driving schedule represents near dock (2-6 miles), local (6-20 miles), and regional (20+ miles) drayage port operation. The SCR was inactive for 100% of the near dock cycle, 95% of the local cycle, and 60% of the regional cycle, see Figure 1-2. The NO_x emissions were on the order of 0.3 to 2 g/hp-h (1 to 9 g/mi) as much as 10 times higher than the 2010 standards. It has been show that the SCR system also becomes inactive even after hours of operation due to low loads and lean compression ignition combustion. Thus, the current diesel 2010 solution for low duty cycle activity (like at ports) is very poor where a NG solution can make significant improvements for NO_x emissions, and a reduction in carbon emissions (carbon dioxide), but at a slight penalty in equivalent gallon diesel fuel economy.

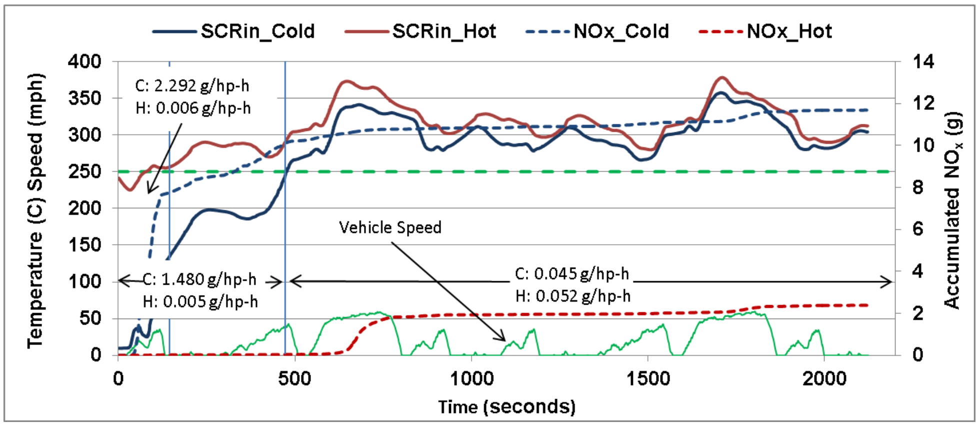
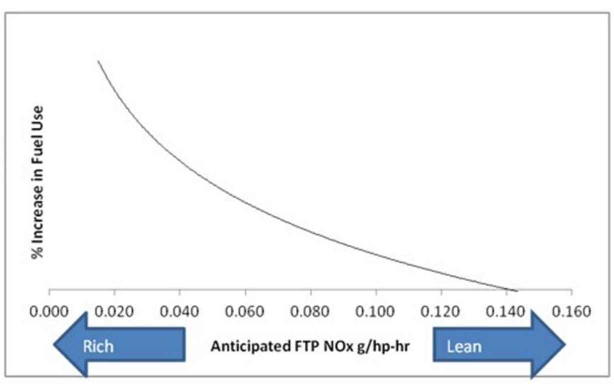


Figure 1-2 In-use emissions from a heavy duty truck tested on UCR's chassis dyno

1.3 Fuel economy

Fuel consumption and emissions are a tradeoff due to the science of combustion. Figure 1-3 shows the NO_x emissions change with changes in fuel consumption for a typical spark ignited engine. As NO_x is reduced from 0.14 to 0.02 g/hp-h fuel consumption increases a known amount. This is a result of the stoichiometric combustion of fuels. Advanced catalysts can be used to reduce NO_x from its baseline levels, but trying to reduce NO_x within a fixed SI combustion system will come at a penalty of increased fuel consumption.



(Source CWI)

Figure 1-3 NOx emissions versus fuel consumption tradeoffs during certification testing

[2] Patrick Couch, John Leonard, TIAX Development of a Drayage Truck Chassis Dynamometer Test Cycle, Port of Long Beach/ Contract HD-7188, 2011

1.4 Objectives

The goals of project are to evaluate the ISL G NZ 8.9 liter ultra-low NO_x NG vehicle emissions, global warming potential, and fuel economy during in-use conditions. Given the low NO_x concentrations expected, additional measures were implemented to quantify NO_x emissions at and below 0.02 g/bhp-hr emissions levels. This report is a summary of the approach, results, and conclusions of ultra-low NO_x NG vehicle evaluation.

2 Approach

The approach for this demonstration vehicle evaluation includes in-use testing on a chassis dynamometer, emissions measurements with UCRs mobile emission laboratory (MEL), improvements to the NO_x measurement method and a representative selection of in-use test cycles. One of the difficulties in quantifying NO_x emissions at the levels proposed in this project (90% lower than the 2010 certification level ~ 0.02 g/bhp-hr) is the measurement methods are approaching their detection limit to accurately quantify NO_x emissions. This section describes the test article, laboratories and the upgrades performed to quantify NO_x emissions at and below 90% of the 2010 emission standard.

2.1 Test article

2.1.1 Engine

The test article is the ISL G NZ 320 Cummins Westport Inc. (CWI) Natural Gas engine (SN = 73779339), see Table 2-1 for specifics and Appendix F for additional details. The engine was initially certified as a 0.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM based on the family number ECEXH0540LBH found on the engine label and the executive order (EO) published on the ARB website, see Figure F-1 Appendix F. CWI developed this engine as a ultra-low NO_x demonstration engine where the NO_x emissions have been further reduced to 0.02 g/bhp-hr (90% below the 2010 NO_x emissions standard). A second, recently released EO for the near zero configuration with engine family GCEXH0540BH, also on the CARB website and provided from CWI shows the lower NO_x standard is 0.02 g/bhp-hr and the actual certified value was 0.01 g/bhp-hr, see Figure F4 Appendix F. This evaluation is to quantify the in-use NO_x emissions in relationship to the 0.02 g/bhp-hr demonstration level.

Table 2-1 Summary of selected main engine specifications

Mfg	Model	Year	Eng. Family	Rated Power (hp @ rpm)	Disp. (liters)	Adv NO_x Std g/bhp-h [1]	PM Std. g/bhp-h
CWI	ISL G NZ	2014	ECEXH0540LBH	320 @ 2100	8.9	0.02	0.01

[1] The family ECEXH0540LBH is on the engine label given its year of manufacture. The engine tested was produced under the ECEX… label but was later certified and upgraded to the GCEX… label. The engine tested is thus, based on the GCEX label and represents a 0.02 g/bhp-hr NO_x standard, see Appendix F Figure 4 for details.

2.1.2 Test Fuel

California pipeline fuel was used for this study which represents typical Natural Gas available in Southern California. The fuel properties were measured during the emissions testing and are presented in Table 2-2. Fuel samples were collected from the vehicle prior to testing. Three vehicle refuelings (Agua Mansa Station, Riverside CA) were required to complete the work and three fuel samples were collected. Due to sample container issues, only the November 20th sample collected was analyzed as presented in Table 2-2. It is expected the pump NG fuel was consistent over the five days of testing.

Table 2-2 Fuel properties for the local NG test fuels utilized

Property	Molar %	Property	Molar %
Methane	94.65	Pentane	0.01
Ethane	3.87	Carbon dioxide	0.35
Propane	0.41	Oxygen	0.00
Butane	0.08	Nitrogen	0.63

1 Based on these fuel properties the HHV is 1-42.5 BTU/ft3 and the LHV is 939.9 BTU/ft3 with a H/C ratio of 3.905, a MON of 132.39 and a carbon weight fraction of 0.745 and a SG = 0.58, see Appendix E for laboratory results. Note these results meets the US EPA 40 CFR Part 1065.715fuel specification for NG fueled vehicles.

2.1.3 Vehicle inspection

Prior to testing, the vehicle was inspected for proper tire inflation and condition, vehicle condition, vehicle securing, and the absence of any engine code emission faults. The vehicle inspection and securing met UCR's specifications. Cummins Westport Inc. had a service person on site to make sure fault codes were absent prior to and during emissions testing. All tests were performed with-in specification and without any engine code faults. Thus, the results presented in this report are representative of a properly operating vehicle, engine, and aftertreatment system.

2.1.4 Test cycles

The test vehicle utilized an 8.9 liter NG engine which is available for three typical vocations in the South Coast Air Basin, 1) goods movement, 2) bus, and 3) refuse[3]. The engine was provided to UCR in its refuse hauler application which is one of the more common uses for the 8.9 liter engine, see Figure 2-4. In order to characterize emissions from this engine over the rage of in-use applications, goods movement and bus cycles were also tested. UCR tested the vehicle following the three port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS), the Central Business District (CBD) bus cycle, and the AQMD Refuse cycle, see Appendix B for details. These cycles are representative of Sothern California driving. Some cycles are short (less than 15 minutes) where double or triple cycles (2x or 3x) cycles are recommended in order capture enough PM mass to quantify emissions near 1 mg/bhp-hr. The UDDS was performed twice (UDDSx2) and the CBD was performed three times (CBDx3) where the emissions represent the average of the cycle.

Table 4 Summary of statistics for the various proposed driving cycles

Day	Distance (mi)	Average Speed (mph)	Duration (sec)
Near Dock	5.61	6.6	3046
Local	8.71	9.3	3362
Regional	27.3	23.2	3661
UDDSx2	11.1	18.8	2122
CBDx3	3.22	20.2	560
AQMD Refuse	4.30	7.31	2997

[1] Hot UDDS was performed as a double cycle (2x) and a single (1x) for the cold tests. The CBD was performed as a triple (3x) test. The refuse cycle includes a compaction element where no distance is accumulated, but emissions are counted with a simulated compaction cycle, see Appendix B for details.

[3] Cummins Westport, California Energy Commission Merit Review- ISL G Near Zero, December 2, 2015

2.1.5 Work calculation

The reported emission factors presented are based on a g/bhp-hr and g/mi basis (g/mi are provided in Appendix E). The engine work is calculated utilizing actual torque, friction torque, and reference torque from broadcast J1939 ECM signals. The following two formulas show the calculation used to determine engine brake horse power (bhp) and work (bhp-hr) for the tested vehicle. Distance is measured by the chassis dynamometer and the vehicle broadcast J1939 vehicle speed signal. A representative ISL G NZ 320 engine lug curve is provided in Figure 2-1.

$$Hp_{\_i} = \frac{RPM_{\_i}\left(Torque_{actual\_i} - Torque_{friction\_i}\right)}{5252} * Torque_{reference}$$

Where:

Hp_i	instantaneous power from the engine. Negative values set to zero
RPM_i	instantaneous engine speed as reported by the ECM (J1939)
Torque_actual_i	instantaneous engine actual torque (%): ECM (J1939)
Torque_friction_i	instantaneous engine friction torque (%): ECM (J1939)
Torque_reference	reference torque (ft-lb) as reported by the ECM (J1939)

$$Work = \sum_{i=0}^{n} \frac{Hp_{\_i}}{3600}$$

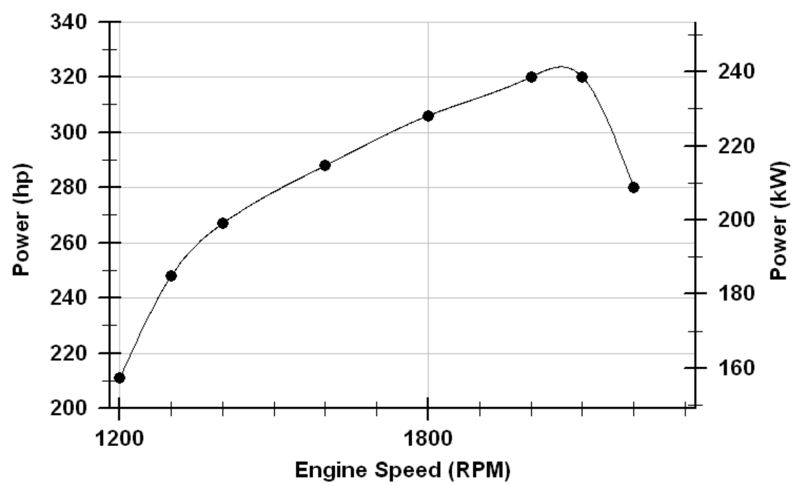


Figure 2-1 Published ISLG 8.9 Natural Gas engine power curve

Figure 2-2 and Figure 2-3 show the measured power and work for each of the tests performed on the refuse vehicle. The engine is certified on the FTP type of cycle where the average power is around 82 Hp and estimated at 24.7 bhp-h, also shown in Figure 2-2 and Figure 2-3. The UDDS, regional (DPT3) and the CBD test cycles represent power near (but lower) than the FTP certification cycle. The near dock (DPT1), local (DPT2), and refuse (RTC) cycles showed much lower power with the DPT1 being the lowest (as shown by previous studies). Previous testing of the low power from the DPT1 cycle resulted in high diesel NO_x emissions because the SCR operating temperatures were never obtained.

The measured work for the all the cycles (except the CBD (lower), RTC, and the regional (DPT3 much higher)) were close to the certification FTP estimated work (Note the hot-UDDS was higher because a double cycle was performed where the cold-UDDS was performed as a single UDDS test). In general the cycles selected are representative of in-use conditions and certification testing. It is expected the results from this study will be very representative for real world emission factors for the test article.

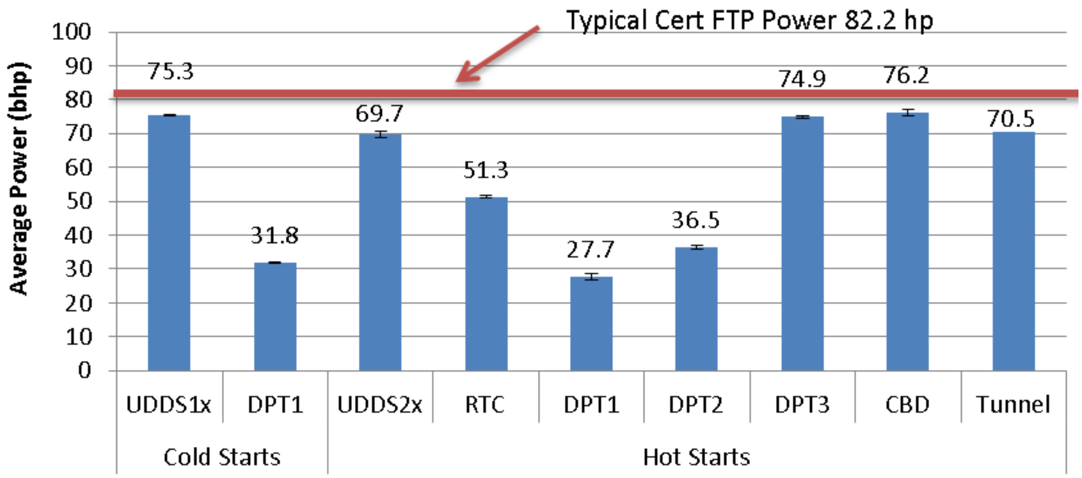


Figure 2-2 Power from the various tests with 1 stdev error bars

[1] The tunnel blank (TB) was performed without the vehicle operating. To calculate a work specific TB comparison, the TB test utilized the power and work value of a single hot-UDDS test to provide context of the measurement detection limits.

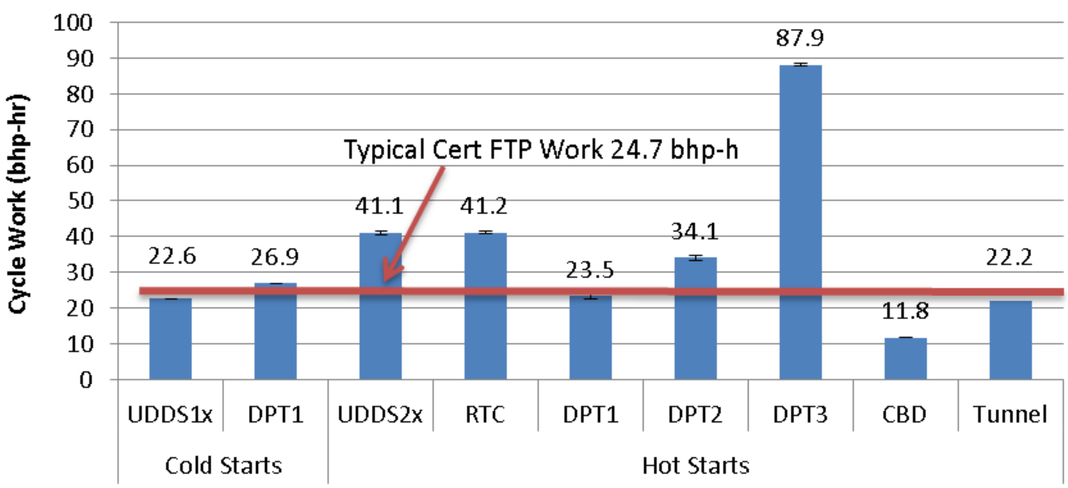


Figure 2-3 Work from the various tests with 1 stdev error bars

[1] The TB was performed without the vehicle operating. To calculate a work specific TB comparison, the TB test utilized the power and work value of a single hot-UDDS test to provide context of the measurement detection limits.

2.2 Laboratories

The testing was performed on UC Riverside's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside CA just east of the South Coast Air Quality

Management District (AQMD). This section describes the chassis dynamometer and emissions measurement laboratories used for evaluating the in-use emissions from the demonstration vehicle. Due to challenges of NO_x measurement at 0.02 g/bhp-hr, additional sections are provided to introduce the measurement improvements.

2.2.1 Chassis dynamometer

UCR's chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy duty vehicles, see Figure 2-4. The design incorporates 48" rolls, vehicle tie down to prevent tire slippage, 45,000 lb base inertial plus two large AC drive motors for achieving a range of inertias. The dyno has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horse power at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common. See Appendix D for more details.

2.2.1.1 Test weight

The ISL G NZ 320 engine is installed in a refuse hauler chassis with a GVW of 62,000 lb, VIN 3BPZX20X6FF100173. The representative test weight for refuse haulers operating in the south coast air basin is 56,000 lb[4]. The testing weight of 56,000 lb was also utilized during previous testing of refuse haulers with diesel and NG engines by UC Riverside and WVU [4 and 5]. For this testing program UCR utilized a testing weight of 56,000 lb for all test cycles (refuse, CBD, UDDS, and port cycles).

Figure 2-4 UCR's heavy duty chassis eddy current transient dynamometer

[4] Wayne Miller, Kent C. Johnson, Thomas Durbin, and Ms. Poornima Dixit 2014, In-Use Emissions Testing and Demonstration of Retrofit Technology, Final Report Contract #11612 to SCAQMD September 2014.

[5] Daniel K Carder, Mridul Gautam, Arvind Thiruvengada,m Marc C. Besch (2013) In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines, Final Report Contract #11611 to SCAQMD July 2014.

2.2.1.2 Coast down

UCR utilizes a calculation approach for the coast down settings of the chassis dynamometer. This approach is also used by other testing facilities and has been shown to be representative of in-use operation, see Appendix G for a more detailed discussion. The test weight of 56,000 lb resulted in a power of 117.42 Hp at 50 mph with the calculated dynamometer loading coefficients of A = 397.73642, B = -2.43E-14 and C = 0.193166. See calculation methods in Appendix G for more details.

2.2.2 Emissions measurements

The proposed NO_x measurement (at 0.02 g/bhp-hr) are approaching the detection limits for the traditional dilute CVS measurement method. This section discussed the traditional and upgraded methods recommended for the ultra-low NO_x evaluation. This section also provides a section on the calculations utilized, additional measurements needed (ie. Trace analyzers and exhaust flow) and an evaluation of the upgraded methods in comparison to the tradition methods.

2.2.2.1 Traditional method

The approach used for measuring the emissions from a vehicle or an engine on a dynamometer is to connect UCR's heavy-duty mobile emission lab (MEL) to the total exhaust of the diesel engine, see Appendix C for more details. The details for sampling and measurement methods of mass emission rates from heavy-duty diesel engines are specified in Section 40, Code of Federal Regulations (CFR): Protection of the Environment, Part 1065. UCR's unique heavy-duty diesel MEL is designed and operated to meet those stringent specifications. MEL is a complex laboratory and a schematic of the major operating subsystems for MEL are shown in Figure 2-4. The accuracy of MEL's measurements has been checked/verified against ARB's[6] and Southwest Research Institute's [7, 8] heavy-duty diesel laboratories. MEL routinely measures Total Hydrocarbons (THC), Methane (CH_4), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), and Particulate Matter (PM) emissions from diesel engines. Design capabilities and details of MEL are described in Cocker et al[4,9]. Samples can be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

The traditional NO_x measurements include a 600 heated chemiluminescent detector (HCLD) from California Analytical Inc. (CAI) configured to sample from the CVS tunnel during real time and ambient and dilute bag measurements following automated routines of the MEL laboratory. The samples are collected from the CVS dilute tunnel through an acid treated filter to

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[6] Cocker III, D. R., Shah, S. D., Johnson, K. C., Zhu, X., Miller, J. W., Norbeck, J. M., Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter, Environ. Sci. Technol. **2004**, 38, 6809-6816

[7] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., Measurement Allowance Project – On-Road Validation. Final Report to the Measurement Allowance steering Committee.

[8] Johnson, K.C., Durbin, T.D., Cocker, III, D.R., Miller, W.J., Bishnu, D.K., Maldonado, H., Moynahan, N., Ensfield, C., Laroo, C.A. (2009) On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle, Atmospheric Environment 43 (2009) 2877–2883

[9] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., *Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions*, Environmental Science and Technology. **2004**, 38, 2182-2189

prevent measurement interferences from ammonia (NH_3) concentrations. The acid treated filters were replaced daily.

In addition to the regulated emissions, the laboratory was equipped to measure particle size distribution (PSD) with TSI's Engine Exhaust Particle Sizer (EEPS) model 3090, particle number (PN) with a TSI 3776 condensation particle counter (CPC), soot PM mass with AVL's Micro Soot Sensors (MSS 483), NH_3 emissions with an integrated real-time tunable diode laser (TDL) from Unisearch Associates Inc. LasIR S Series, and a batched low level nitrous oxide (N_2O) emissions with a Fourier Transform Infrared Spectrometer (FTIR). The PN measurement system used a low cut point CPC (2.5 nm D50) because of the large PN concentrations reported below the PMP protocol CPC 23 nm measurement system (10, 11, and 12). The EEPS spectrometer displays measurements in 32 channels total (16 channels per decade) and operates over a wide particle concentration range, including down to 200 particles/cm3.

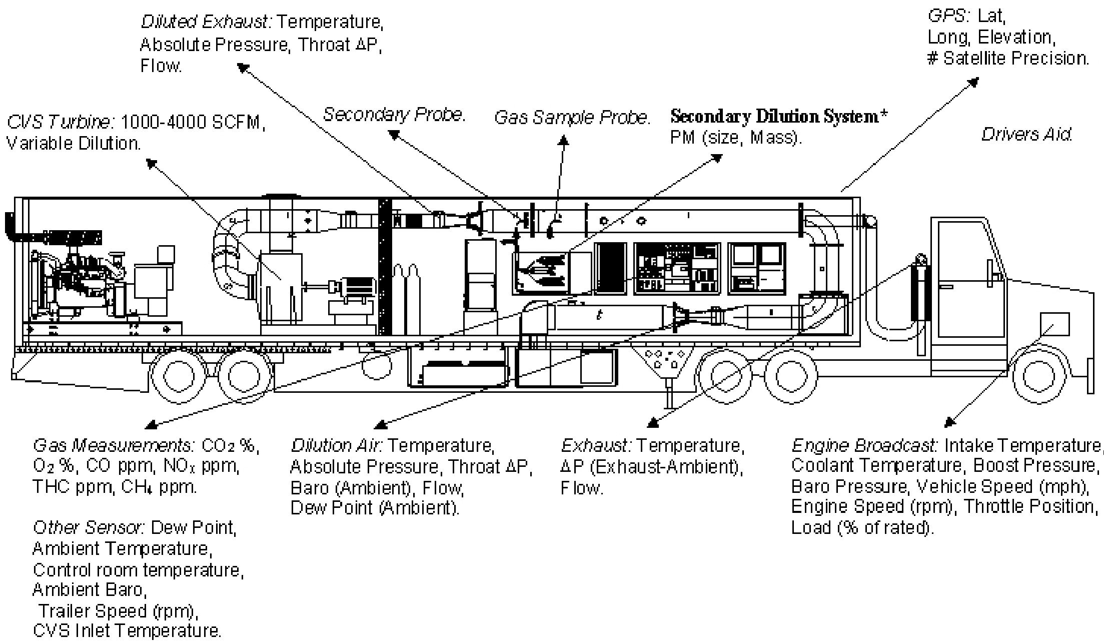


Figure 2-5 Major Systems within UCR's Mobile Emission Lab (MEL)

2.2.2.2 NO_x Method upgrades

Three NO_x upgrade methods were considered for this project. These included 1) real-time raw sampling and exhaust flow measurements, 2) real-time ambient second by second corrections, and 3) advanced trace type analyzer bag measurements. The new measurement methods required instrumentation upgrades which are discussed below.

Raw NOx measurements

The raw NO_x measurements utilized a 300 HCLD CAI analyzer which sampled raw exhaust through a low volume heated filter and heated sample line. The low volume design was considered to improve the response time of the analyzer with the exhaust flow measurement. The heated filter was acid treated to minimize NH_3 interference with the NO_x measurement. A real-time high speed exhaust flow meter (100 Hz model EFM-HS Sensors Inc) was used to align NO_x

concentration with real time exhaust flow measurements. The EFM-HS was correlated with UCR dual CVS system prior to testing to improve the accuracy between the raw and dilute CVS methods and eliminate exhaust flow biases from propagating through the comparison.

Trace level NOx analyzer

A trace level chemiluminescence NO-NO_2-NO_x analyzer model 42C manufactured by Thermo Environmental Instruments Inc (TECO) was used for the real-time ambient measurements and the low level bag analysis. This analyzer has been operating with-in CE-CERT's atmospheric research laboratories for ambient NO_x quantification for several years. This analyzer was calibrated and integrated specially for this ultra-low NO_x project. The span on the instrument was set to 600 ppb and showed a signal to noise ratio about an order in magnitude lower than the traditional (600 HCLD) analyzer. The signal averaging was reduced from 30 seconds to 1 second and showed a $T_{10\text{-}90}$ and a $T_{90\text{-}10}$ just over 10 seconds (slightly higher than the specifications of 40 CFR Part 1065). The slightly slower time constant should not impact the gradual transients expected during real-time ambient measurements or bag concentrations. Although this trace analyzer does not meet the requirements of 1065, it does provide a good assessment of NO_x emissions below 1 ppm with an ambient trace type NO_x analyzer.

2.2.2.3 Calculation upgrades

The calculations for the traditional and improved methods are presented in this section. The calculations are in agreement with 40 CFR Part 1065, but are presented in a condensed version to draw observation differences without the details of working in molar flow rates as per 40 CFR Part 1065.

Table 2-3 NO_x measurement methods traditional and upgraded

Type	Analyzer	Meth. ID	Description
Traditional	600 HCLD dil 600 HCLD amb	M1	Modal NO_x with ambient bag correction
Traditional	600 HCLD dil 600 HCLD amb	M2	Dilute bag NO_x with ambient bag correction
Upgrade	300 HCLD raw	M3	Raw NO_x no ambient bag correction
Upgrade	600 HCLD dil TECO amb	M4	Modal dilute NOx with ambient real time correction
Upgrade	TECO dil TECO amb	M5	Trace analyzer dilute bag with trace ambient bag correction

Traditional Methods:

The traditional NO_x measurement methods are described in the next two equations. The first equation is the real-time modal measurement corrected for the ambient bag concentration and real time dilution factor, Method 1 (M1). The second traditional equation (M2) is based on dilute bag and ambient bag concentrations and an integrated dilution factor over the cycle.

$$NO_{x\_m1} = \sum_{i=1}^{n} (Q_{cvs_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{m\_i} - C_a * \left(1 - \frac{1}{DF_i}\right)\right)$$

Where:

NO_{x_m1}	the Method 1 NO_x measurement method (g/cycle)
Q_{cvs_i}	is the instantaneous CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_{m_i}	is the instantaneous NO_x concentration measured with the dilute NO_x 600 HCLD CAI analyzer
C_a	is the ambient bag NO_x concentration measured by the 600 HCLD CAI analyzer
DF_i	instantaneous dilution factor

$$NO_{x\_m2} = (Q_{cvs\_ave} * \Delta t) * \rho_{NO_x} * \left(C_d - C_a * \left(1 - \frac{1}{DF_{\_ave}}\right)\right)$$

Where:

NO_{x_m2}	the Method 2 NO_x measurement method (g/cycle)
Q_{cvs_ave}	is the average CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_d	is the dilute bag NO_x concentration measured with the dilute NOx 600 HCLD CAI analyzer
C_a	is the ambient bag NO_x concentration measured by the 600 HCLD CAI analyzer
DF_{ave}	average dilution factor

Upgraded Methods:

The upgraded NOx measurement methods are presented in the next three equations. These upgrades included new analyzers, sample lines, sample filters, and exhaust flow measurement systems. For Method 3 (M3) there is no ambient correction. For Method 4 (M4) the real time dilute NOx is corrected for ambient real time NOx on a second by second basis. For Method 5 (M5) the trace NOx analyzer is used to measure the dilute bag and ambient bags (similar to Method 2).

$$NO_{x\_m3} = \sum_{i=1}^{n} (Q_{exh_i} * \Delta t_{\_i}) * \rho_{NO_x} * (C_{m\_i})$$

Where:

NO_{x_m3}	the Method 3 NO_x measurement method (g/cycle)
Q_{exh_i}	is the instantaneous exhaust flow measured in the tail pipe
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_{m_i}	is the dilute bag NO_x concentration measured with the dilute NO_x 300 HCLD CAI analyzer

$$NO_{x\_m4} = \sum_{i=1}^{n} (Q_{cvs_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{m\_i} - C_{a\_adv\_i} * \left(1 - \frac{1}{DF_i}\right)\right)$$

Where:

NO_{x_m4}	the Method 4 NO_x measurement method (g/cycle)
Q_{cvs_i}	is the instantaneous CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065

C_{m_i}	is the dilute bag NO_x concentration measured with the dilute NO_x 600 HCLD CAI analyzer
C_{a_adv}	is the trace ambient bag NOx concentration measured by the TECO trace NO_x analyzer
DF_i	instantaneous dilution factor

$$NO_{x\_m5} = (Q_{cvs\_ave} * \Delta t) * \rho_{NO_x} * \left(C_{d\_adv} - C_{a\_adv} * \left(1 - \frac{1}{DF_{\_ave}}\right)\right)$$

Where:

NO_{x_m5}	the Method 5 NO_x measurement method (g/cycle)
Q_{cvs_ave}	is the average CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_{d_adv}	is the dilute bag NO_x concentration measured by the TECO trace NO_x analyzer
C_{a_adv}	is the ambient bag NO_x concentration measured by the TECO trace NO_x analyzer
DF_{ave}	average dilution factor

2.2.3 Method evaluation

One of the main contributing factors to the issue with the traditional CVS sampling system is the magnitude of the ambient concentration has on the calculation. Table 2-4 lists the 10th, 50th, and 90th average ambient, dilute modal, and raw tailpipe measured percentile concentrations. The 50th percentile raw, dilute, and ambient NO_x concentration were 0.55 ppm, 0.17 ppm, and 0.07 ppm respectively.

As discussed previously, the ambient concentration is subtracted from the dilute concentration prior to calculating the mass based emissions. This subtraction is typically a larger number minus a small number. At the 0.02 g/bhp-hr emission level, the ambient concentration is now at the same levels as the dilute measured value. The ambient concentration was found to be 54% of the total measured dilute concentration at the 50th percentile measured concentration, see Table 2-4. The ambient corrected NOx concentration (C_{a_cor}) utilized in the dilution measurements is the product of ambient NO_x concentration and an inverse ratio of the dilution factor, see equation below. If we divide the C_{a_cor} by the dilute NOx measured we get a ratio that is representative of the ambient percent of total NOx. Figure 2-6 shows the ratio in a histogram plot and more than half the data is above 0.6 suggest that most of the measurements meeting the 0.02 g/bhp-hr were only twice that of ambient concentrations. This ratio gives the reader a feel for the influence ambient has at and below 0.02 g/bhp-hr NOx emissions.

Table 2-4 Cycle averaged raw, dilute, and ambient measured concentrations (ppm) statistics

Percentile	Amb	Dilute [1]	Raw [1]	C_{a_cor}/Dil %
10th	0.234	0.632	6.533	105%
50th	0.070	0.168	0.554	54%
90th	0.021	0.033	0.070	10%

[1] With the cold starts removed, the dilute and raw 10th, 50th, and 90th would be 0.326, 0.146, and 0.031 ppm for the dilute concentration and 2.115, 0.450, and 0.069 ppm for the raw concentration, respectively.

The results show a 10th, 50th and 90th percentile (C_{a_cor}/C_d) ratio of 10%, 54% and 105%, respectively. This suggest more than ½ of the measurements were sampled where the dilute concentration was 50% of the ambient corrected (C_{a_cor}) concentration. The low concentrations measured by dilute methods will impact all the methods except for M3 that utilizes the raw sampling approach where no dilution correction is needed.

$$C_{a\_cor} = C_a * \left(1 - \frac{1}{DF_{\_ave}}\right)$$

Where:

C_{a_cor}	is the ambient NOx concentration factor used in M1
C_a	is the ambient bag NOx concentration
DF_{ave}	cycle average dilution factor (typically 20-30)
$\left(1 - \frac{1}{DF_{\_ave}}\right)$	dilution factor term (varied from 0.95 to 0.98 in this study)

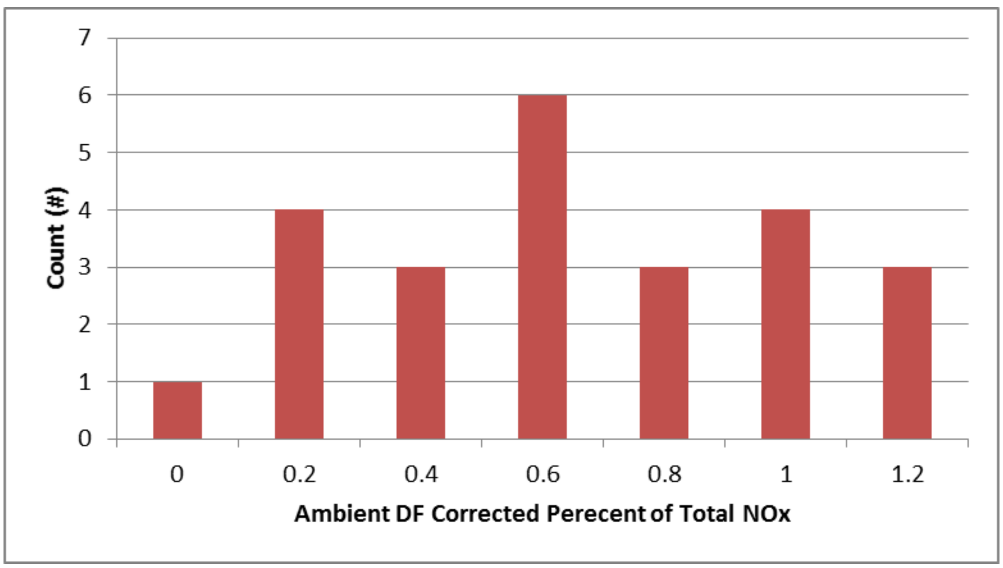


Figure 2-6 Ambient fraction of dilute NO_x concentration distribution

The real-time concentrations for each cycle is also important where observations suggest a few NO_x spikes of 20-30 times the average values were the basis of the cycle average concentrations. Section 4 provides additional discussions on the real-time transient NO_x measurements. It is important to understand that the real-time NO_x spikes will impact the M1, M3, and M4 measurements since these utilize real-time signals where M2 and M5 are integrated bag signals.

The average mean difference in average emissions between the methods is shown in Table 2-5 with M1 as the reference method. For M2 the average NO_x emissions was very similar to M1 (only 5% higher on average, but varied from higher to lower from cycle to cycle). M3 was slightly lower (-18% on average), but was consistently lower except for the CBD tests. Further investigation of the CBD tests shows one of the M1 tests had a negative emission rate due a high ambient bag concentration compared to the modal dilute concentration. This negative value was not an outlier, but a real measurement difficulty at these emission levels. The M4 average NO_x emission rate was notably higher (and relatively more variable) and for M5 the average was significantly lower for all tests compared to the M1 traditional method.

The M4 utilized real time ambient concentrations for real time correction of the background calculation. The trace analyzer utilized show some short term drift that didn't appear to be related to ambient concentration changes. Additional investigation is needed, but is outside the scope of this effort. The researchers suggest the M4 method will have more variability as a result and could be the cause for the higher mean difference.

The M5 utilized the trace NO_x analyzer for bag measurements. Surprisingly the M5 method showed a much lower mean value. Investigations were carried out to see about analyzer drift or stability and no issues were found during the bag analysis time spans.

Table 2-5 NO_x emission average percent difference from Method 1

Trace	M2	M3	M4	M5
UDDS1x	-17%	-40%	96%	-87%
DPT1	31%	-42%	-8%	-99%
UDDS2x	7%	-13%	21%	-70%
RTC	4%	-21%	111%	-7%
DPT1	-21%	-11%	25%	-14%
DPT2	3%	-20%	25%	-61%
DPT3	12%	-22%	27%	-72%
CBD	19%	23%	32%	16%
Ave	5%	-18%	41%	-49%
Stdev	17%	20%	40%	42%

A comparison of the statistical significance between the traditional M1 and other methods is provided in Table 2-6. The two tailed paired t-test and f-test results suggest the two traditional methods do not have statistically different means or different variances at 95% confidence, see Table 2-6 (M2 p-value >> 0.05 for both). The upgraded methods showed a different result that varies. The M3 (raw exhaust flow approach) mean difference is not statistically significant at 95% confidence (M3 p-value > 0.06) but is at the 90% confidence. The M4 (RT ambient correction) and M5 (trace bag evaluation) upgraded methods both have statistically different means (p-value < 0.05 for both).

Table 2-6 Comparison to traditional Method 1 measurement (modal dilute NO_x)

Method	t-test	f-test
M2	0.521	0.998
M3	0.060	0.152
M4	0.021	0.141
M5	0.001	0.104

Each of the added methods (M3, M4, and M5) may have some possible implementation issues that need to be considered in order to evaluate the comparative results. The M3 measurement showed good alignment between the measured NOx signal and the exhaust flow signal. The majority of the NOx mass emissions resulted from a few large spikes, as discussed in Section 4. These NOx spikes were found to represent more than 80% of the total emission factor. Closer inspection shows that the NOx concentration and exhaust flow spike occurred simultaneously and were usually a result of a rapid acceleration from idle.

For the M4 approach (real-time NOx ambient correction) the analyzer had a slight zero stability issue over the 20-40 minute test cycle not found during the short 3 minute bag analysis. As such, the drift may be the result of the M4 poor method comparison.

The low M5 method may represent the best approach with very accurate bag measurements for both the ambient and dilute bag measurements with a trace type NOx analyzer with a larger sample cell. The drift issue suggested for the M4 measurement didn't appear to be a factor during the short bag analysis, but additional tests should be performed to evaluation. As such, this method may have performed the best, but additional testing is suggested to evaluate this method on future testing opportunities at 0.02 g/bhp-hr.

In summary the M1, M2, and M3 appear to be the most reliable where the M3 results are more consistent at the extremely low concentrations measured. M4 and M5 require further investigation with lower zero drift instrumentation.

3 Results

This section describes the results from the ISL G NZ 8.9 liter ultra-low NO_x NG engine. The results are organized by gaseous emissions followed by PM, particle size distribution, greenhouse gases, and fuel economy. The emission factors presented in g/bhp-hr for comparison to the certification standard. Emissions in g/mile are provided in Appendix E. Error bars are represented by single standard deviations due to the relatively large magnitude of the error bars in relationship to the low emission levels measured for several species (three repeats were performed where the 95% confidence interval multiplier for the single standard deviation is 3.182).

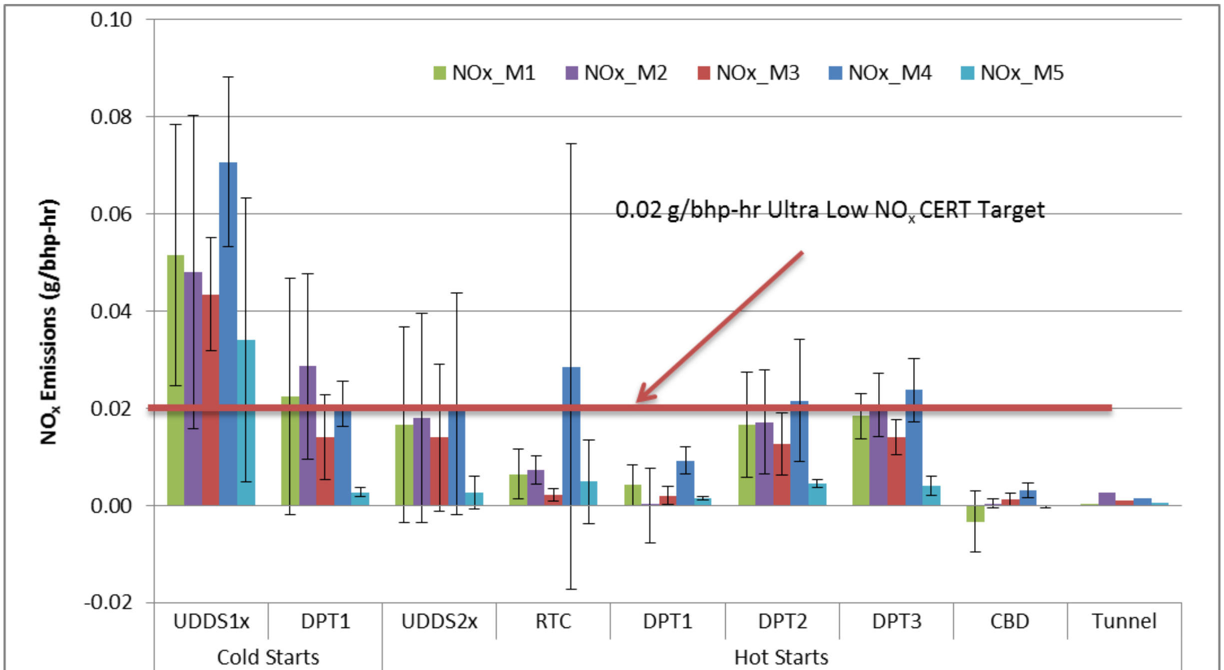
The UDDS cycle is the representative test cycle for comparisons to the engine certification FTP cycle where the other cycles (port, refuse, and bus) provide the reader a feel for the in-use comparability to low duty cycles, cruise conditions, and other vocational specifics of the real world. As such, the results will be presented in each sub-section within the context of the test cycle.

3.1 Gaseous emissions

3.1.1 NOx emissions

The NO_x emissions are presented in Figure 3-1 for each of the methods evaluated and for all the test cycles performed. The NO_x emissions were below the demonstration 0.02 g/bhp-hr emissions targets for the UDDS, DPT1 (hot and cold), and the CBD for all measurement methods. The local and regional port cycles (DPT2 and DPT3) NO_x emissions were below the improved methods but at and below the standard for the traditional methods. The cold start emissions were higher than the hot tests when comparing between like tests (UDDS cold vs hot and DPT1 cold vs hot) and averaged at 0.043 g/bhp-hr for the UDDS test cycle (M3).

In general, the NO_x emissions are below the ISL G NZ 2016 NO_x certification standard of 0.02 g/bhp-hr for all tests and below the in-use NTE standard of 0.03 g/bhp-hr. The reported certification value listed on the ARB EO is 0.01 g/bhp-hr which is slightly lower than the M3 measurements (0.014 g/bhp-hr) shown for the UDDS hot test cycle, Figure 3-1. Deeper investigation shows one of the three hot UDDS tests was statistically higher (M3 = 0.009, 0.002, 0.030 g/bhp-hr). A similar trend was also found for the other four methods where the third point was much higher than the other two points. If the third point was eliminated the average for the hot UDDS would be just under the EO certification value reported by CWI (M3 = 0.005 g/bhp-hr). The test-to-test variability shown by the large error bars in Figure 3-1 was investigated where real-time analysis suggest the variability is not from low measurement issues, but appears to be the results of the vehicle variability. Section 4 provides a discussion on real-time investigation.

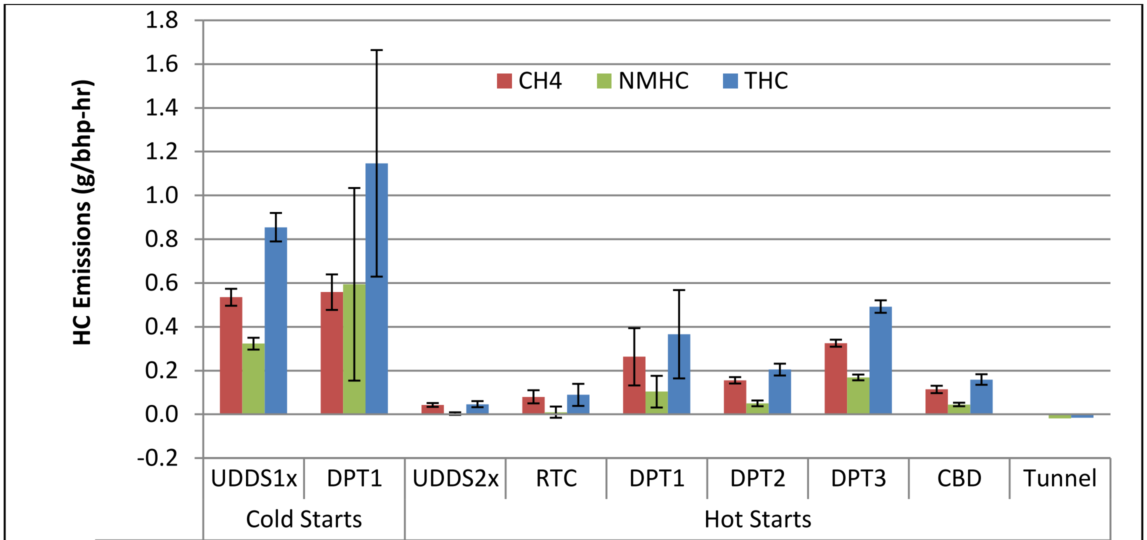


	UDDS1x	DPT1	UDDS2x	RTC	DPT1	DPT2	DPT3	CBD	Tunnel
	Cold Starts		Hot Starts						
NOx_M1	0.052	0.022	0.017	0.006	0.004	0.017	0.018	-0.003	0.000
NOx_M2	0.048	0.029	0.018	0.007	0.000	0.017	0.021	0.000	0.003
NOx_M3	0.043	0.014	0.014	0.002	0.002	0.013	0.014	0.001	0.001
NOx_M4	0.071	0.021	0.021	0.029	0.009	0.022	0.024	0.003	0.001
NOx_M5	0.034	0.0	0.003	0.005	0.001	0.005	0.004	0.000	0.001

Figure 3-1 Measured NOx emission for the various test cycles

3.1.2 Other gaseous emissions

The hydrocarbon emissions (THC, CH_4, and NMHC) are presented in Figure 3-2. The HC are highest for the cold start tests compared to the hot tests where the regional port cycle (PDT3) showed the highest HC emissions. For all the hot tests the NMHC was below the standard but just above the reported certification value except for the regional port cycle. The NMHC was typically lower than CH_4 emission as one would expect for a NG fueled vehicle. The CH_4 emissions are lower than the certification results presented in Appendix F Figure F-4 (0.04 vs the FEL level of 0.65 g/bhp-hr). Also the CH_4 emissions for the refuse hauler are significantly lower (6.4 g/mi vs 0.26 g/mi) than previously tested NG reuse haulers with the 2010 certified NG 8.9 liter engine. The lower CH_4 emissions may be a result of the closed crankcase ventilation (CCV) improvement over previous versions of this engine, see Appendix F for details.



	UDDS1x	DPT1	UDDS2x	RTC	DPT1	DPT2	DPT3	CBD	Tunnel
	Cold Starts		Hot Starts						
CH4	0.535	0.558	0.043	0.080	0.263	0.155	0.325	0.114	0.004
NMHC	0.323	0.594	0.003	0.010	0.104	0.050	0.168	0.045	-0.019
THC	0.855	1.147	0.046	0.090	0.366	0.205	0.492	0.159	-0.015

Figure 3-2 Hydrocarbon emission factors (g/bhp-hr)

Figure 3-3 shows the CO emissions on a g/bhp-hr basis and Figure 3-4 shows the un-regulated NH_3 emissions on a g/bhp-hr basis. The CO emissions ranged between 1.3 to 5.3 g/bhp-hr for the cold start near dock (PDT1) and regional (DPT3) test cycles, respectively. The distance specific emissions ranged from 4.2 to 24.3 g/mi for the regional (PDT3) and the cold start UDDS test cycles. Previous testing of the ISG vehicle show similar CO emissions ranging from 14.4 to 19.2 g/mi (CBD and UDDS test cycles and same test weights).

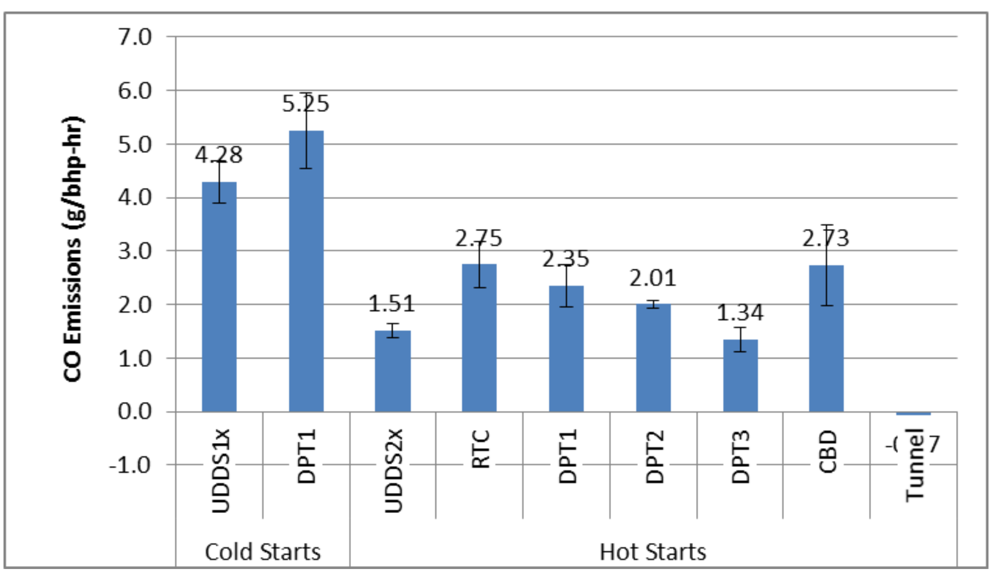


Figure 3-3 CO emission factors (g/bhp-hr)

The NH_3 emissions ranged from 0.43 to 0.94 g/bhp-hr for the hot UDDS and regional (DPT3) cycles. The distance specific emissions varied from 1.16 g/mi to 5.27 g/mi for the regional and CBD test cycles. The NH_3 emissions are slightly higher than previous ISL G vehicle where the NH_3 ranged from 1.17 to 2.8 g/mi for the UDDS and RTC cycle as compared to 1.19 and 4.09 g/mi for the ISL G NZ, respectively. The NH_3 concentration varied from 118 ppm (UDDS) to 305 ppm (CBD), see Figure 3-5.

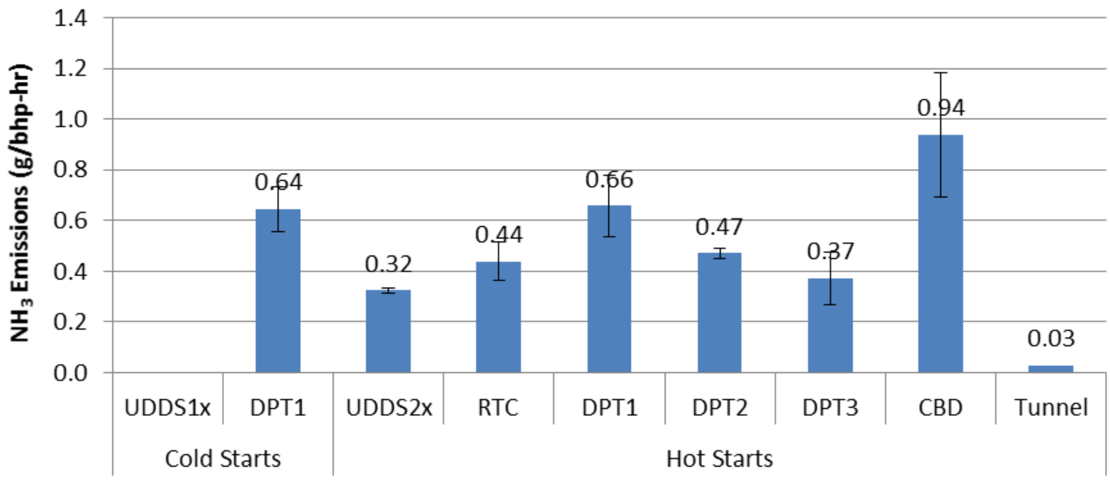


Figure 3-4 Ammonia emission factors (g/bhp-hr)

[1] NH_3 measurements for the cold UDDS test stopped working during the first hill where the system may have over ranged. The cold start UDDS NH_3 results are estimated at 20% higher than the hot-UDDS test.

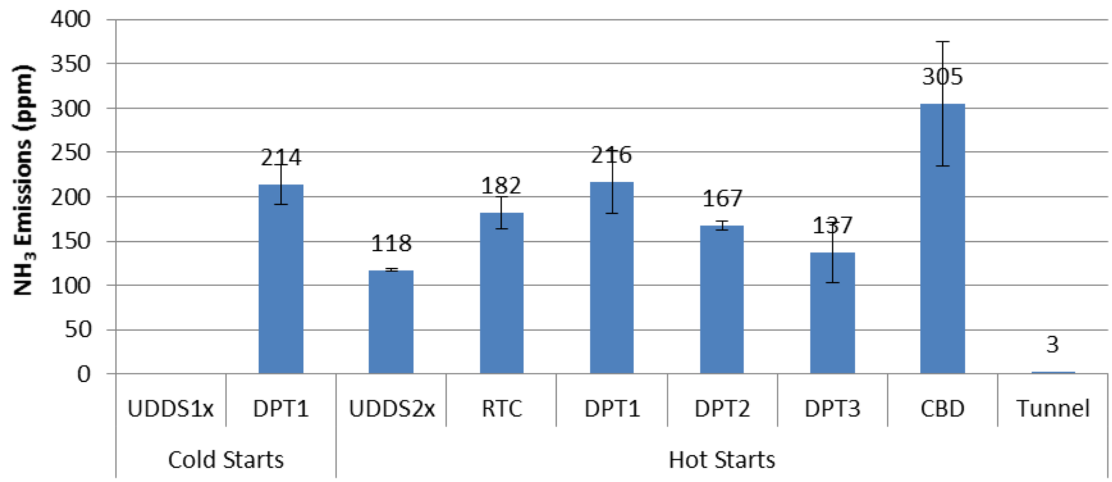


Figure 3-5 Ammonia measured tail pipe concentration (ppm)

[1] NH_3 measurements for the cold UDDS test stopped working during the first hill where the system may have over ranged. The cold start UDDS NH_3 results are estimated at 20% higher than the hot-UDDS test.

3.2 PM emissions

The PM emissions for all the tests including the cold start tests was typically 90% below the certification standard and close to UCR tunnel blank value of 0.42 g/bhp-hr (based on UDDS sample time and work), see Figure 3-6. The first regional PM filter weight was statistically higher than the other three (80, 21, 20 ug) where it is suggested something may have burned off the exhaust system that test that may be artifact of previous vehicle operation. If the first PM results was eliminated the DPT3 EF would be reduced from 1.01 mg/bhp-hr to 0.5 mg/bhp-hr. In either case all the EF were well below the certification standard of 10 mg/bhp-hr. Low PM results are expected for a NG fueled engine where previous studies showed similar PM emissions well below 10 mg/bhp-hr.

The measured filter weights were 13 ug with a single standard deviation of 3 ug where the tunnel blank was measured at 5 ug (representative of 0.42 g/bhp-hr using the UDDS sample conditions). As such, the PM emission rates are very low and the shown variability may be a result of measurement detection capability more than vehicle performance between cycles.

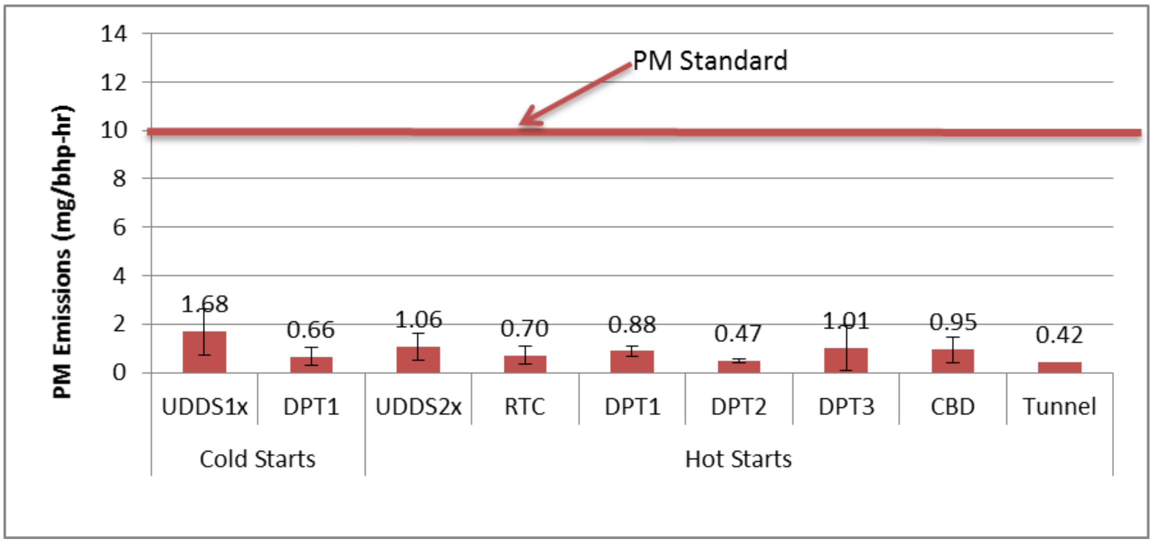


Figure 3-6 PM emission factors (mg/bhp-hr)

[1] Tunnel PM emission factor was based on a tunnel blank and test conditions of the UDDS 2x load conditions for the ISL G NZ test engine.

3.3 PN emissions

The PN emissions (CPC 3772) are shown in Figure 3-7 and Table 3-1 for the test cycles performed. The PN were highest for the high speed regional cycle (DPT3) on a total # basis, but were highest on a #/mi basis for the cold start near dock cycle (PDT1). Since the UDDS cycle is representative of the FTP certification cycle, comparisons to the hot UDDS cycle are presented in Table 3-2 (#/mi basis). The statistical analyses in Table 3-2 were conducted using a 2-tailed, 2 sample equal variance t-test. For the statistical analyses, results are considered to be statistically significant for $p < 0.05$, or marginally statistically significant for $0.05 < p < 0.1$. The near dock port cycle (DPT1) and the UDDS cold start showed statistically significant mean differences where the regional port cycle (DPT 3) showed marginally significant mean difference to the UDDS hot test. The cold start UDDS showed about three times the PN compared to the hot UDDS. The regional cycle showed about 82% more PN compared to the UDDS cycle and the near dock (DPT 1) showed 92% fewer PN. The trash compaction cycle (RTC) and the local port cycle (PDT 2) had similar PN emission rates and did not show statistically different means.

During previous studies with 0.2 g/bhp-hr certified NO_x ISL G engine tested on the near dock and regional port cycles, the PN emissions were $1.9 \times 10^{12} \pm 3.8 \times 10^{11}$ #/mi (11) which was about

92% lower than the ISL G NZ UDDS test cycle results, but about the same as the near dock port cycle. In a second study with the ISL G 8.9 liter engine, the PN emissions were 4×10^{12} for the CBD test cycle (10) which agrees well with the results in this study for the near dock and CBD test cycles. During a similar refuse hauler application of the ISL G engine, the PN emissions for the RTC cycle were 2.5×10^{13}, 5.8×10^{12}, and 2.0×10^{12} #/mi for the curbside, transit, and compaction portions of the RTC test cycle, respectively (12) which compare well with the PN from the ISL G NZ results. Late model diesel engines equipped with DPFs show PN emissions that range from 1.3×10^{11} to 0.7×10^{11} for on-road UDDS and cruise type of tests (18). In general the PN emissions for the ISL G NZ are mixed in comparison to the ISL G with some higher and some about the same. The ISL G NZ and ISL G both show higher PN emissions compared to diesel vehicles equipped with DPFs.

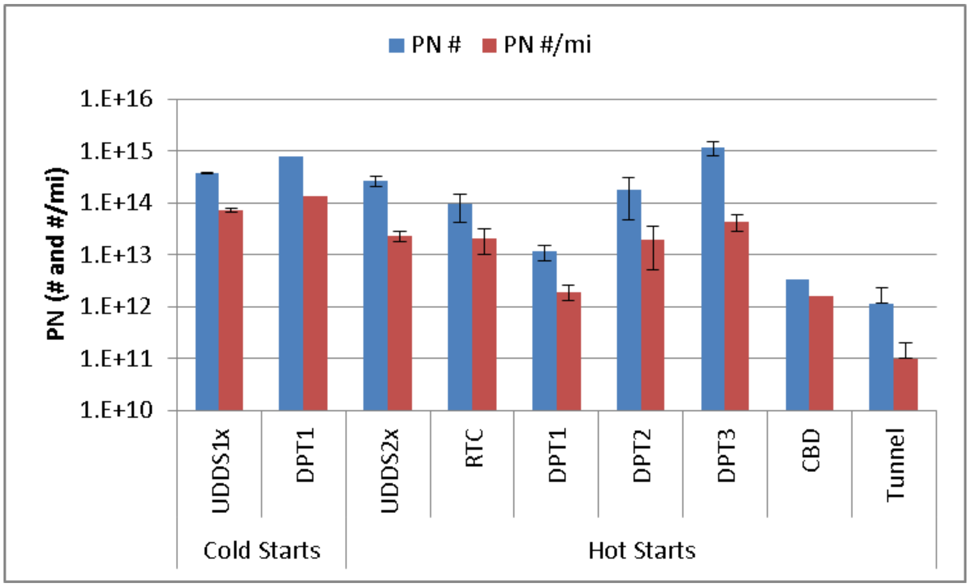


Figure 3-7 Particle number emissions (# and #/mi)

[1] Note the PN presented are based on CVS dilute measurements without sample conditioning (no volatile particle catalytic stripper system) and a D50 of 3 nm (CPC 3776). These PN values will be higher than those presented by the PMP system which uses a 3790A counter (24 nm D50 cut diameter and a volatile particle catalytic stripper system).

Table 3-1 PN Emissions from the ISL-G NZ 8.9 liter engine for various cycles

	PN #		PN #/mi	
Trace	ave	stdev	ave	stdev
CS_UDDS1x	3.80E+14	1.90E+13	7.25E+13	5.22E+12
CS_DPT1	7.87E+14		1.36E+14	
UDDS2x	2.66E+14	6.21E+13	2.37E+13	5.39E+12
RTC	9.49E+13	5.20E+13	2.12E+13	1.12E+13
DPT1	1.16E+13	3.83E+12	1.96E+12	6.25E+11
DPT2	1.83E+14	1.35E+14	2.01E+13	1.50E+13
DPT3	1.16E+15	3.46E+14	4.30E+13	1.51E+13
CBD	3.42E+12		1.62E+12	
Tunnel	1.15E+12	1.15E+12	1.02E+11	1.02E+11

[1] CS stands for cold start and Tunnel stands for tunnel blank. Stdev is a single standard deviation.

Table 3-2 Statistical comparison to the UDDSx2 test cycle

Cycle	t-test	f-test	mean % dif
CS UDDS	0.012	0.870	206%
RTC	0.492	0.388	-11%
DPT1	0.002	0.027	-92%
DPT2	0.721	0.230	-15%
DPT3	0.104	0.227	82%

[1] Unpaired two tailed sample equal variance t-test and mean % difference from the UDDSx2 test cycle

3.4 Ultrafines

The ultrafine PSD (as measured by the EEPS) are shown in Figure 3-8 on a log-log scale concentration basis as measured in the dilute CVS. The cold start UDDS and the regional (DPT3) cycles showed the highest particle number concentration at 10 nm particle diameter of all the traces. The higher PSD for the cold UDDS and regional cycle are a result of PN spikes under different conditions. The cold start UDDS PSD PN spike occurred during the cold portion and for the hot regional cycle (DPT3) the spike occurred during the cruise. The secondary peak at 105 nm particle diameter was highest for the same two cycles and the CBD. DPT1 showed the lowest PSD and was typically below the tunnel blank concentrations. During previous testing on the ISL G 8.9 liter engine the PSD showed a similar bi-modal PSD at 10 nm and 110 nm (10, 11, and 12). Diesel vehicles equipped with a DPF only show a single mode of operation (when not in a DPF regeneration) for the same UDDS and port cycles tested on the ISL G NZ vehicle (2).

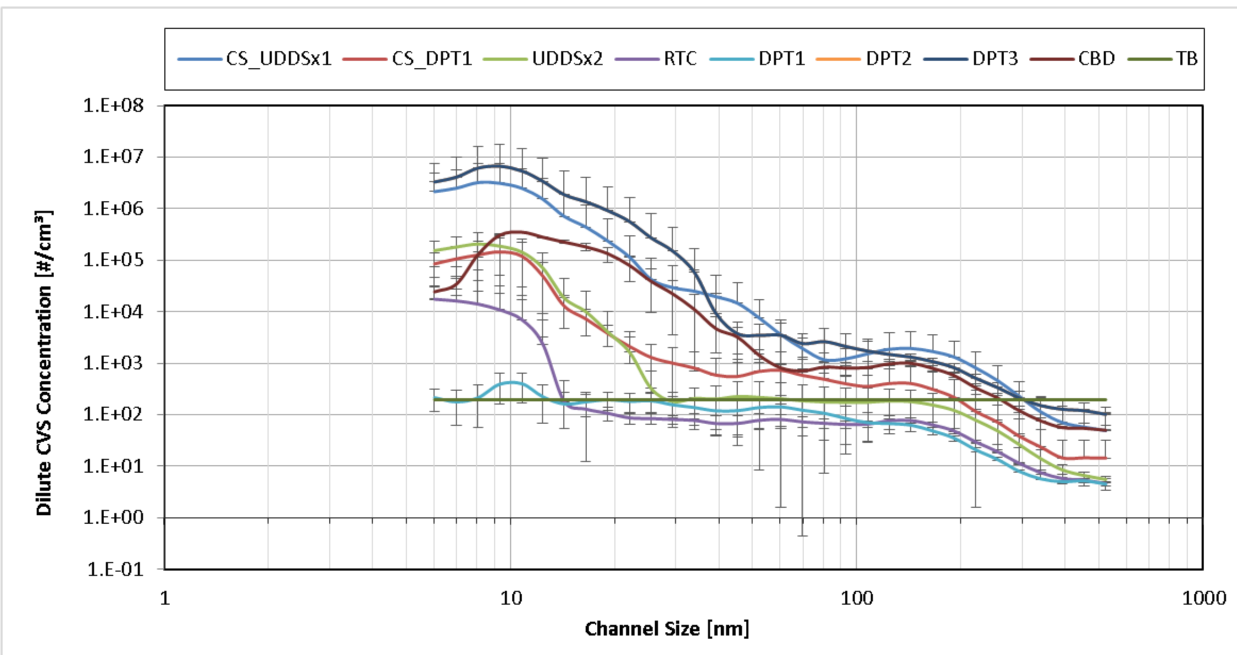


Figure 3-8 EEPS ultrafine PSD measurements for each of the test cycles

3.5 Greenhouse gases

The greenhouse gases include CO_2, CH_4 and N_2O and are reported here to characterize the vehicles global warming potential (GWP). The GWP calculations are based on the intergovernmental panel on climate change (IPCC) values of 25 times CO_2 equivalent for CH_4 and 298 times CO_2 equivalent for nitrous oxide (N_2O), IPCC fourth assessment report - 2007. The global warming potential is provided in Table 3-3 on a g/bhp-hr basis (see Appendix E for g/mi basis). The CH_4 and N_2O emissions are low and represent 5% for the cold start tests and around 1-2% for the hot start tests.

Greenhouse gases from vehicles are also found in PM emissions for their absorption of solar radiation. The main species of the PM responsible for solar absorption is called black carbon (BC). BC is a short lived climate forcer and is not grouped with the CO_2 equivalent method, and is treated here separately. UCR quantified the BC emissions (referred to as equivalent black carbon eBC) from the vehicle with its AVL micro soot sensor 483 (MSS) which measures the PM soot or eBC. Table 3-3 lists the soot PM for each cycle and the ratio of soot/total PM emissions. The results suggest less than 10% of the PM measured for all the cycles except the regional port cycle are BC and during the regional cycle up to 22% of the total PM measured is BC. Additional analysis showed that the measured average concentration ranged between 2-3 ug/m3 when corrected for water interferences (as reported by manufacturer) the concentration was~ 1ug for all tests. The low concentrations are at the detection limits of the MSS instrument and suggests the measured BC cannot be quantified accurately, but may suggest BC is not significant for the ISL G NZ NG engine.

Table 3-3 Global warming potential for the ISLG NZ vehicle tested (g/bhp-hr)

Trace	CO_2	CH_4	N_2O	GWP ($CO_{2\,eq}$)	CO_2 /GWP	Soot	Soot/$PM_{2.5}$
UDDS1x	546.8	0.53	0.062	578.5	0.95	0.05	3%
DPT1	627.0	0.56	0.090	667.7	0.94	0.02	3%
UDDS2x	548.9	0.04	-	555.0	0.99	0.06	5%
RTC	577.0	0.08	-	584.0	0.99	0.01	1%
DPT1	649.8	0.26	-	661.4	0.98	0.07	8%
DPT2	597.0	0.16	0.027	608.9	0.98	0.1	22%
DPT3	549.3	0.33	0.024	564.4	0.97	0.01	1%
CBD	576.1	0.11	0.034	589.0	0.98	0.04	4%

[1] N_20 samples were not collected on the hot UDDS, RTC, and DPT1 due to scheduling details. PM Soot measurements were near the detection limits of the MSS-483 measurement system. The MSS soot signal was corrected for a 1 ug/1% water interference factor as reported by AVL.

3.6 Fuel economy

The fuel economy of the NG vehicle is evaluated by comparing the CO_2 emissions between cycles where the higher the CO_2 the higher the fuel consumption. CO_2 is also regulated by EPA with a standard as performed with the FTP and SET test cycles. The certification like cycle (UDDS) showed the lowest CO_2 emissions and were below 555 g/bhp-hr (FTP standard) for both the cold start and hot start tests. The NG vehicle CO_2 emissions varied slightly between cycles where only the near dock cycle (DPT1) showed a statistically higher CO_2 emission rate. The average CO_2 for all the cycles was 584 g/bhp-hr, and 565 g/bhp-hr with the PDT1 cycle removed. The CO_2 standard and certification value is 555 g/bhp-hr and 465 g/bhp-hr respectively for this displacement engine, see Figure F1 Appendix F. The standard is the target and the certification value is the value measured by the manufacturer. It is suggested the higher in-use CO_2 value (ie in the chassis vs on a test stand) could be a result of additional losses in the chassis where the certification test occurs with the engine on a test stand.

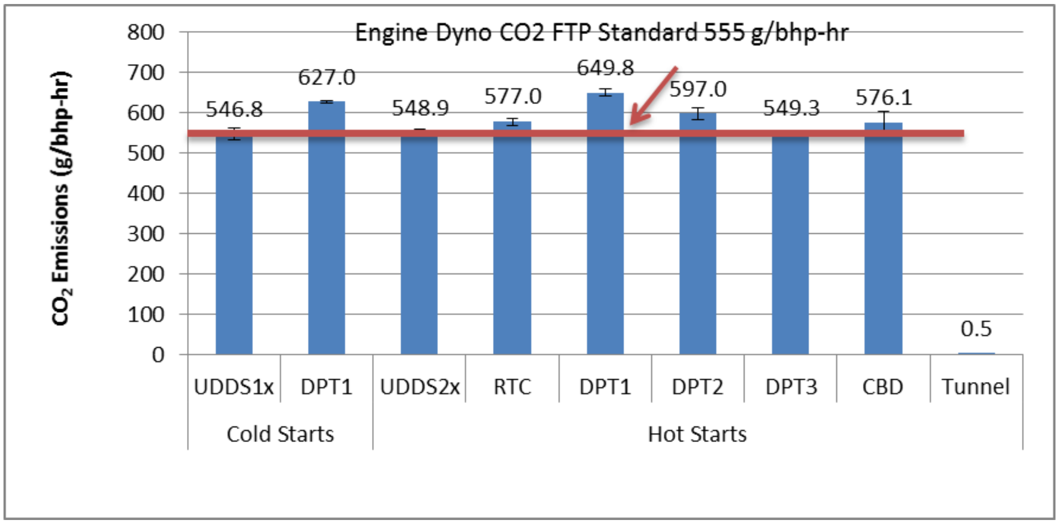


Figure 3-9 CO_2 emission factors (g/bhp-hr)

The ISL G-NZ MPG on a diesel gallon equivalent (MPG_{de}) basis (assuming 2863gNG/gallon diesel (14)) ranges from 4.5 MPG_{de} for the regional port cycle (DPT3) to 2.5 MPG_{de} for the CBD cycle. During previous testing, the previous ISL G 8.9 L fuel economy was found to be 2365 g/mi on a chassis dynamometer at 56,000 GVW following the UDDS test cycle.

4 Discussion

This section discusses investigation into the real-time data to characterize the impact of the cold start and transient NO_x emissions.

4.1 Transient emissions

Figure 4-1 shows the real-time NO_x mass emission rate (g/sec) for the three repeated UDDS cycles. Test 0813 and 1020 had large NO_x spikes, one near the beginning of the test and one near the end of the test where test ID 0915 had only small spikes which are not apparent in Figure 4-1. This indicates that NOx emissions are essentially zero except during sharp accelerations. Figure 4-2 shows the accumulated NO_x emissions as a function of time. The results in Figure 4-2 show the impacts the large and small spikes have on the accumulated NO_x emissions. Test 0915 and 1020 were very similar except for the large spike near the end of the 1020 test.

Figure 4-3 shows the percent of total NOx accumulate as a function of time. The one large spike for test 1020 represented 90% of the total emissions. If the single NOx spike did not occur, the EF for the triplicate cycle would have been close to 0.005 g/bhp-hr instead of the 0.014 g/bhp-hr reported. Figure 4-4 shows the real time NOx emission rate (g/s) exhaust flow, engine RPM, and engine power at the time where the spike occurred. The NOx spike appears to be occurring at the transition from idle to loaded conditions. The figure shows that NOx emission rate and exhaust flow are lined up well suggesting there is not a measurement issue but a real event. In general the transient nature of the emissions suggest the NOx emission are low and are typically below 0.02 g/bhp-hr when good control of the engine stoichiometry is maintained.

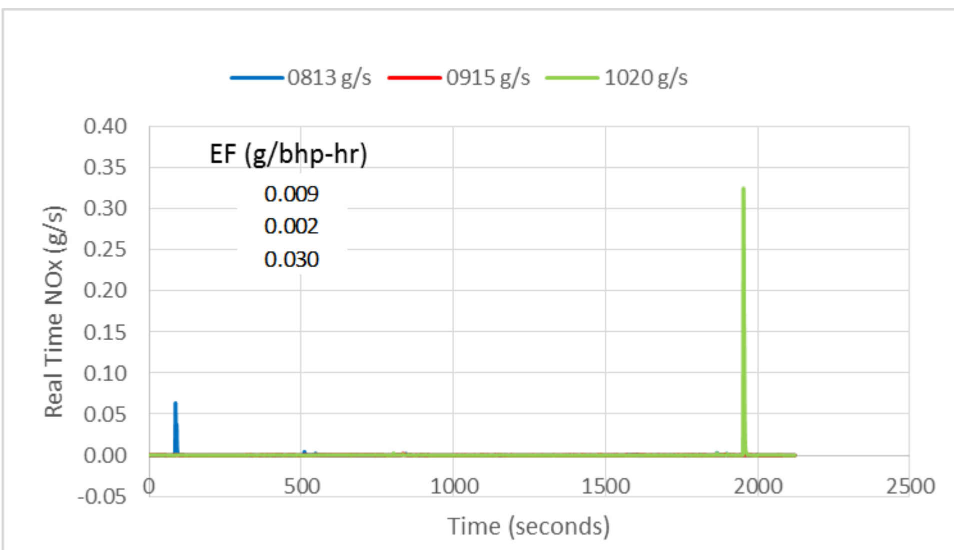


Figure 4-1 Real-time mass rate NOx emissions (g/sec) UDDS cycles

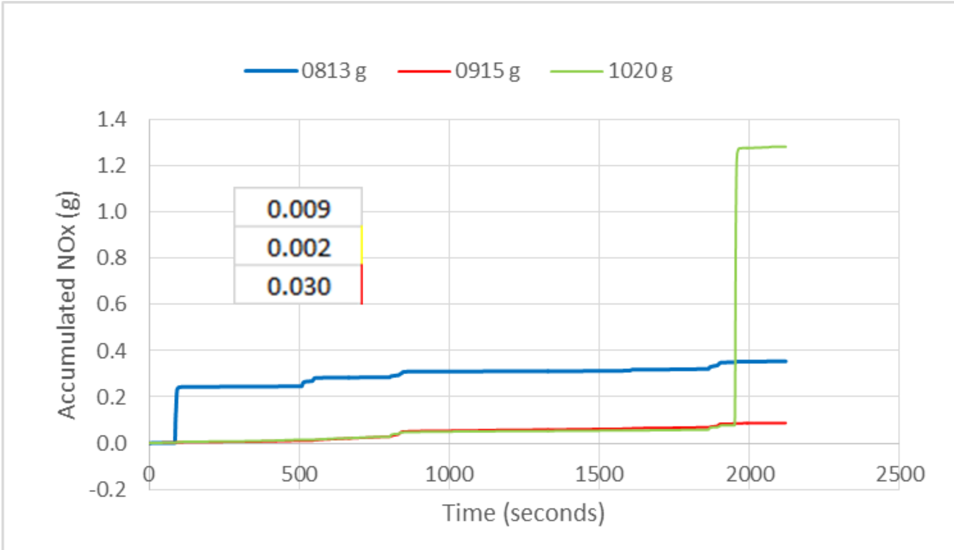


Figure 4-2 Accumulated mass NOx emissions UDDS cycles

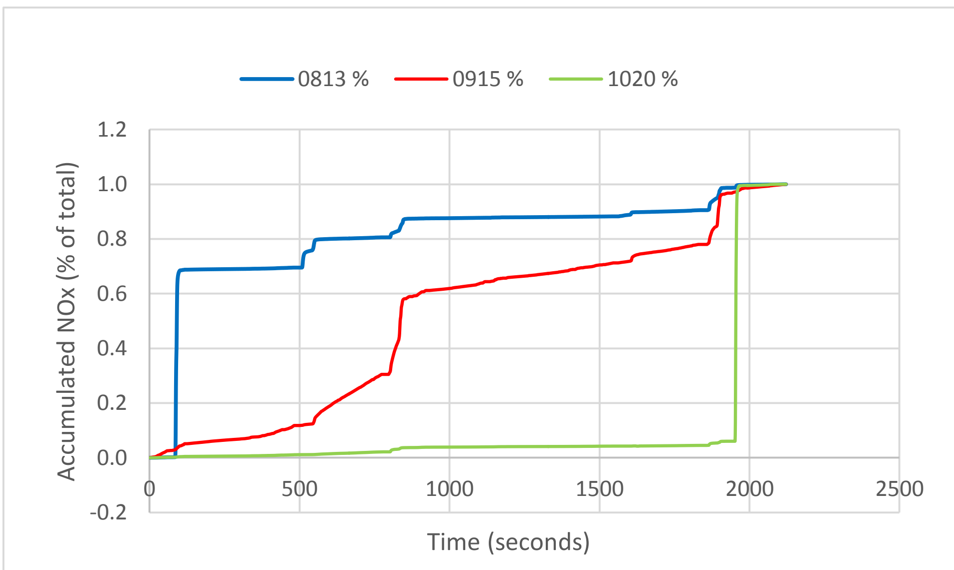


Figure 4-3 Real time NOx emissions (percent of total)

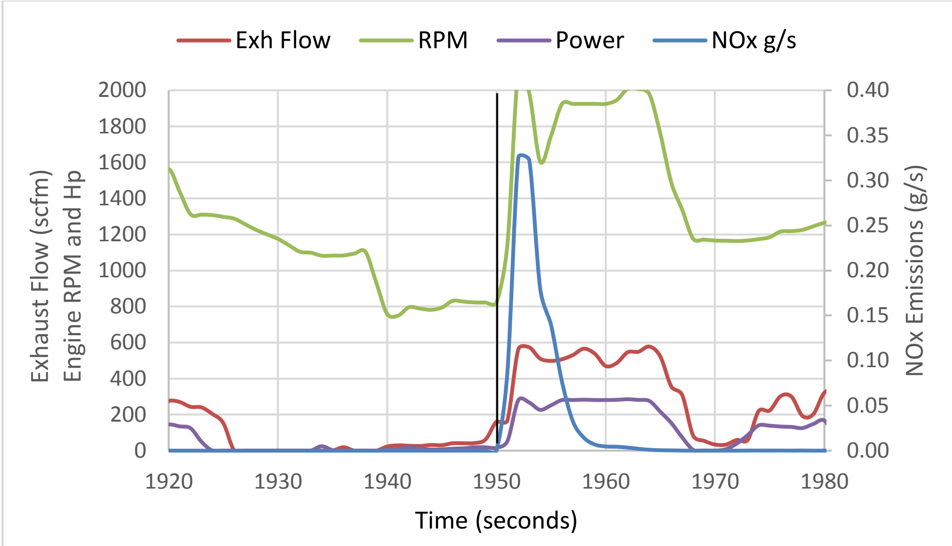


Figure 4-4 Real time NOx emissions large spike evaluation

4.2 Cold start emissions

Cold start emissions represented a significant part of the total emissions as one would expect. Figure 4-5 shows the accumulated NO_x (g) and exhaust temperature as a function of time. 90% of the NO_x emissions occurred in the first 200 seconds of the cold start test. The remaining part of the cold UDDS test was very similar to the hot UDDS test. The UDDS hot/cold weighted emissions is 0.0181 g/bhp-hr (weighted as 1/7th of the hot cycle). Given that the cold start lasted 200 seconds out of 1080 seconds (total cycle length) the weighted cold start emissions (1/7th of the hot test) are, thus, based on 200sec/1080sec/7 = 2.6%. This suggests 2.6% of this vehicles in-use emissions are represented by a cold start as defined by how the certification process computes its impact for the regulation process. Also unique to the NG solution, once the catalyst performance is achieved it remains at this high performance unlike the diesel SCR equipped engines where low duty cycle will cause the NOx emissions to increase again.

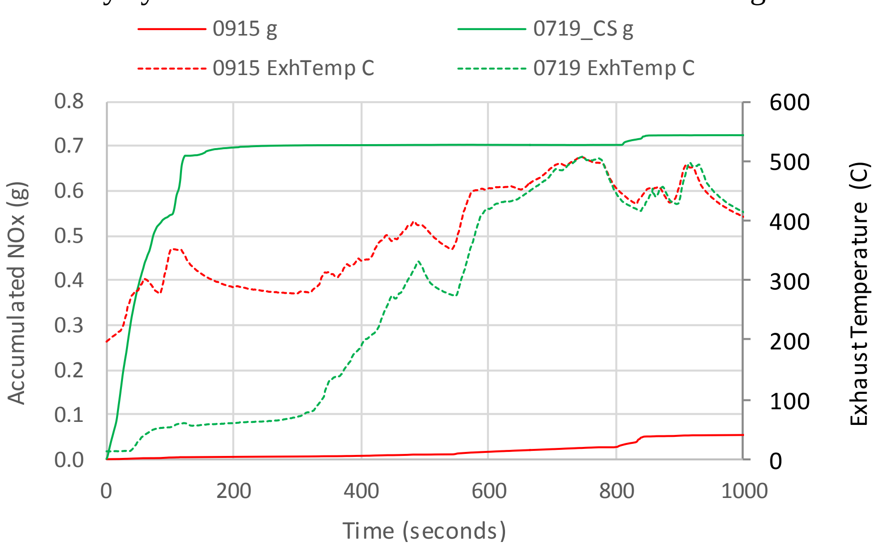


Figure 4-5 Accumulated NOx emissions hot vs cold UDDS comparison

5 Summary and Conclusions

The testing was performed on UC Riverside's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside CA just east of the South Coast Air Quality Management District (SCAQMD). The cycles selected for this study are representative of operation in the South Coast Air Basin and included the urban dynamometer driving schedule, the near dock, local, and regional port cycles, the AQMD refuse cycle, and the central business district cycle.

One of the difficulties in quantifying NO_x emissions at the levels proposed in this research (90% below the 2010 certification level ~ 0.02 g/bhp-hr) is the dilute measurement methods are too close to the detection limit to quantify NO_x emissions at the 5% accuracy expected from the emissions industry. Three upgraded NO_x measurement methods were considered which include a raw NO_x measurement integrated with real time exhaust flow, a real-time ambient correction approach, and a trace level ambient analyzer for accurate bag analysis. In summary the improved methods varied in their success; however, the raw sampling approach was the most accurate and precise over the range of conditions tested.

In general the ISL G NZ 8.9 met and exceeded the target NO_x emissions of 0.02 g/bhp-hr and maintained those emissions during a range of duty cycles found in the South Coast Air Basin. It is expected NG vehicles could play a role in the reduction of the south coast NOx inventory problem given their near zero emission factors demonstrated

The main conclusions can be summarized as (conclusions are based on the Method 2 results unless noted otherwise):

1. The ILS G NZ 8.9 liter NG engine showed NO_x emissions below the 0.02 g/bhp-hr emission target and averaged between 0.014 and 0.002 g/bhp-hr for hot start tests.
2. The cold start tests ranged from 0.043 to 0.014 g/bhp-hr for the UDDS and DPT2 cycles. The UDDS hot/cold weighted emissions was 0.0181 g/bhp-hr for all test cycles performed which is below the certified 0.02 g/bhp-hr emission factor.
3. The NO_x emissions did not increase with lower power duty cycles and showed the opposite trend where the lower power duty cycles showed lower NO_x emissions unlike the diesel counterparts
4. The large NO_x error bars suggest measurement variability, but real-time data shows the variability is isolated to a few NO_x events during rapid tip-in events from accelerations from idle. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle and more gradual accelerations are desired for minimum emissions.
5. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle where more gradual accelerations are desired.
6. The other gaseous and PM emissions were similar to previously measured levels from the 0.2 g/bhp-hr ISL G engine and should not add to any unknown impacts for the use of the NZ engine in the heavy duty fleet.

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Appendix A. Test Log

This Appendix contains detailed test logs recorded during engine and chassis dynamometer testing. The testing was performed on Vehicle ID 2015_016, Project Low NOx 2015, Vehicle VIN = 3BPZX20X6FF100173 with the test mode in Conventional mode. The chassis and vehicle operators were Eddie and Don for all the testing and the instrument operators were Mark, Jade, Danny and Joey.

Date	Test Time	Test Cycle	Test ID	Hp @ 50	Weight	A	B	C
11/16/2015	14:43	Refuse	201511161358	117.42	56000	397.73642	-2.43E-14	0.193166
11/16/2015	14:56	Compaction Cycle	201511161358	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	7:33	UDDS_CS_1x	201511180727	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	8:17	UDDS_x2	201511180813	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	9:22	UDDS_x2	201511180915	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	10:23	UDDS_x2	201511181020	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	12:14	RTC_DPF_NG	201511181280	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	7:22	UDDS_CS_1x	201511190719	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	7:48	Compaction Cycle	warmup	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	8:13	RTC_DPF_NG	201511190809	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	8:54	RTC_DPF_NG	201511190809	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	9:35	RTC_DPF_NG	201511190929	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	10:16	RTC_DPF_NG	201511190929	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	10:58	DTP_1	201511191051	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	12:58	DTP_1	201511191255	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	14:16	DTP_1	201511191412	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	7:19	DTP_1_CS	201511200716	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	8:41	DTP_2	201511200838	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	10:04	DTP_2	201511200959	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	11:24	DTP_2	201511201122	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	7:24	DTP_1_CS	201511230717	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	8:45	DTP_3	201511230840	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	10:18	DTP_3	201511231015	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	12:35	DTP_3	201511231225	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	2:10	CBD	201511231408	117.42	56000	397.73642	-2.43E-14	0.193166

Date	Test Time	Test Cycle	Test ID	Hp @ 50	Weight	A	B	C
11/25/2015	8:27	UDDS_CS_1x	201511250820	117.42	56000	397.73642	-2.43E-14	0.193166
11/25/2015	9:13	CBD	201511250907	117.42	56000	397.73642	-2.43E-14	0.193166
11/25/2015	9:48	CBD	201511250946	117.42	56000	397.73642	-2.43E-14	0.193166

Appendix B. Test Cycle Description

The test vehicle utilizes an 8.9 liter NG engine which is available for three typical vocations in the South Coast Air Basin, 1) goods movement, 2) transit bus, and 3) refuse. As such UCR tested the vehicle following the three drayage type port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS), the Central Business District (CBD) bus cycle, and the AQMD Refuse cycle. These cycles are representative of Sothern California driving vocations used. Some cycles are very short (less than 30 minutes) where double or triple cycles (2x or 3x) cycles are recommended in order capture enough PM mass to quantify emissions near 1 mg/bhp-hr.

Drayage Truck Port (DTP) cycle

TIAX, the Port of Long Beach and the Port of Los Angeles developed the port cycle. Over 1,000 Class 8 drayage trucks at these ports were data logged for trips over a four-week period in 2010. Five modes were identified based on several driving behaviors: average speed, maximum speed, energy per mile, distance, and number of stops. These behaviors are associated with different driving conditions such as queuing or on-dock movement, near-dock, local or regional movement, and highway movements (see Table B-1 for the phases). The data was compiled and analyzed to generate a best fit trip (combination of phases). The best-fit trip data was then additionally filtered (eliminating accelerations over 6 mph/s) to allow operation on a chassis dynamometer.

The final driving schedule is called the drayage port tuck (DPT) cycle and is represented by 3 modes where each mode has three phases to best represent near dock, local, and regional driving as shown in Table B-1, B-2 and Figure B-1. The near-dock (DTP-1) cycle is composed of phase 1, 2, and 3a from Table B-1. This gives the complete near-dock cycle listed in Table B-2. Similarly, for the Local and Regional cycles (DPT-2 and DPT-3) the main difference is phase 3, which changes to 4 and 5 respectively. Phase 1 and 2 remain the same for all three cycles where creep and low speed transient are considered common for all the port cycles. For this testing it is recommended to perform phase 1 through 5 individually and to calculate the weighted emissions from the combined phases for an overall weighing impact.

Table B-1. Drayage Truck Port cycle by phases

Description	Phase #	Distance mi	Ave Speed mph	Max Speed mph	Cycle length
Creep	1	0.0274	0.295	4.80	335
low speed transient	2	0.592	2.67	16.8	798
short high speed transient	3	4.99	9.39	40.6	1913
Long high speed transient	4	8.09	13.07	46.4	2229
High speed cruise	5	24.6	35.04	59.3	2528

Table B-2. Drayage Truck Port cycle by mode and phases

Description	Distance mi	Ave Speed mph	Max Speed Mph	Mode 1	Mode 2	Mode 3
Near-dock PDT1	5.61	6.6	40.6	Creep	Low Speed Transient	Short High Speed Transient
Local PDT2	8.71	9.3	46.4	Creep	Low Speed Transient	Long High Speed Transient
Regional PDT3	27.3	23.2	59.3	Creep	Low Speed Transient	High Speed Cruise

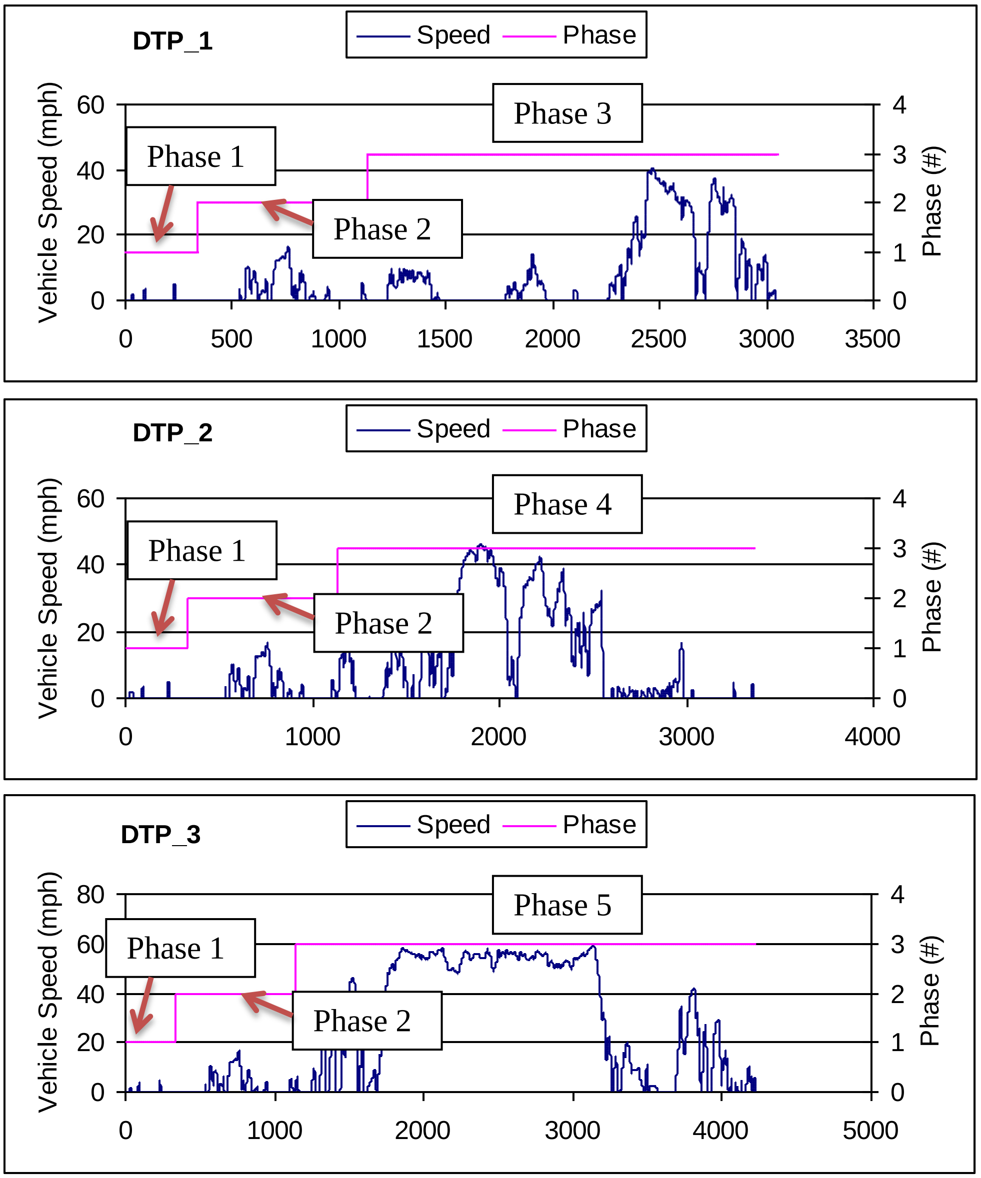


Figure B-1 Drayage truck port cycle near dock, local, and regional

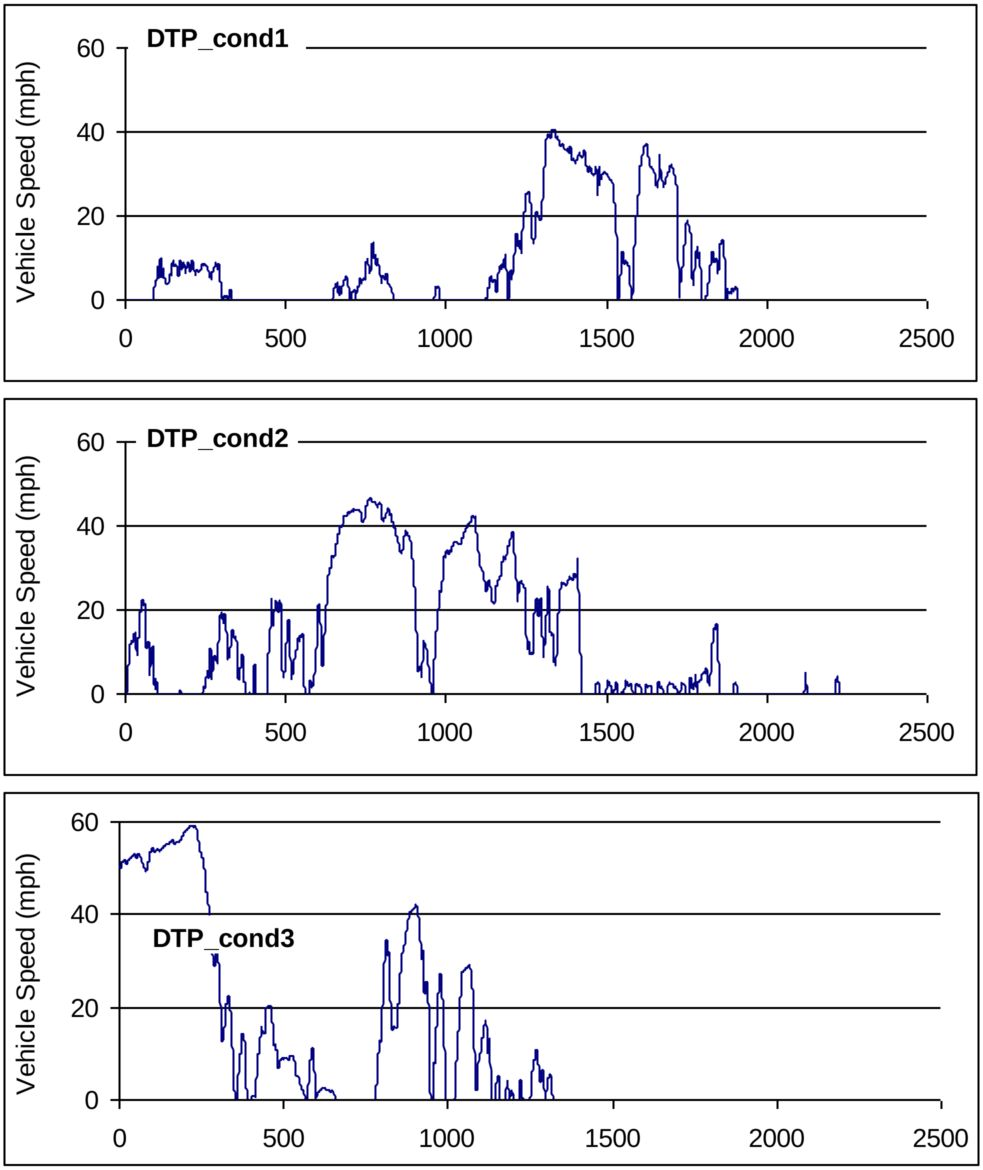


Figure B-2 Drayage truck port cycle conditioning segments consisting of phase 3 parts

Urban Dynamometer Driving Schedule (UDDS) description

The Federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel (HHD) trucks. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph, sample time of 1061 seconds, and maximum speed of 58 mph. The speed/time trace for the HUDDS is provided below in Figures B-3. This cycle was used for all cold start tests as a single test and was performed in duplicate for all hot tests. Duplicates were used to accumulate sufficient mass for the gravimetric measurement method.

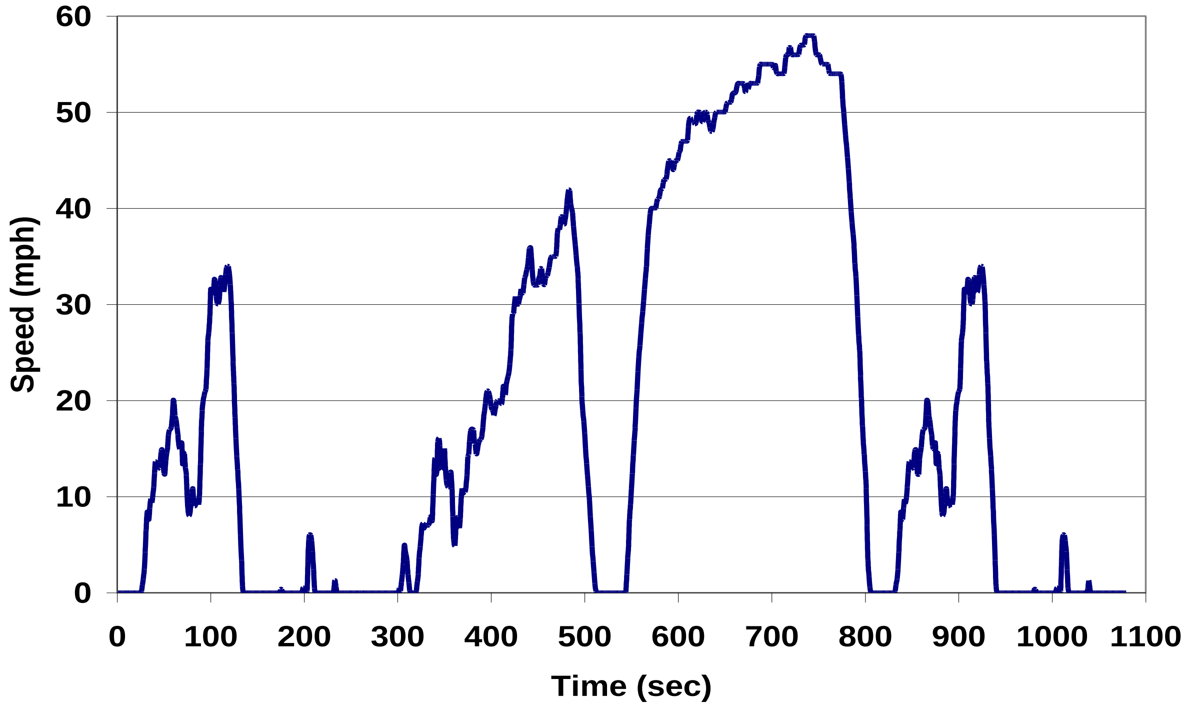


Figure B-3. Speed/Time Trace for a 1xHUDDS cycle for the chassis dynamometer.

The AQMD refuse truck cycle

The AQMD refuse truck cycle (AQMD-RTC) is the same as the WHM-RTC in that the cycle consists of a transport, curbside and compaction operation, with the main difference being the length of time and arrangement of the individual modes. The duration of the AQMD-RTC transport and curbside is 2127 seconds, representing a distance of 4.56 miles and the compaction adds another 760 seconds for a total of 2887 seconds. Figure A-4 shows the vehicle speed vs. time trace for the cycle preparation, transport (phase 1) and curbside (phase 2) portion of the cycle. The curb side pick-up mode is representative of multiple short idle times with frequent stop-and-go operation. The cycle is characterized by frequent accelerations and decelerations. The frequent stop-and-go operation could lead to lower catalytic activity and higher mass tailpipe emissions rates.

Real-world compaction operation was obtained from ECU engine load. It was observed that the engine load varied from 80 to 20 hp in a cyclical manner. The compaction cycle is simulated with the vehicle operating at steady-state speed of 30 mph with an intermittent engine of 80 hp and 20 hp. The total duration of the compaction cycle (phase 3) is 880 seconds, see Figure A-5 for the vehicle speed vs. time trace and axle power loading of the compaction cycle. The emissions are collected for only the stabilized speed which occurs 80 seconds into the trace and ends 40 seconds before the end of the trace for a total of 760 seconds.

Since, the compaction operation does not accrue any driving miles in real-world, the emissions from the compaction cycle are represented on a time-specific basis. Further, in order to represent the distance-specific emissions of the refuse truck operation as a whole, the total mass of emissions from the compaction cycle is added to the transport and curbside emissions divided by the distance of the transport and curbside portion. Thus, it is expected the distance specific emissions on the refuse cycle will be higher than the transport plus curbside emissions since the compaction cycle didn't accumulate any distance.

UCR's MEL was configured with the conditioning and transport plus triple curbside into a signal cycle where the sampling was started at second 526 (Start of Transport Phase 1). After completing Phase 2 (Curbside), the compaction cycle was loaded and the driver brought the vehicle speed up to 30 mph and then the dyno was put in a load cycle mode that oscillated from 20 to 80 hp as shown in Figure B-5.

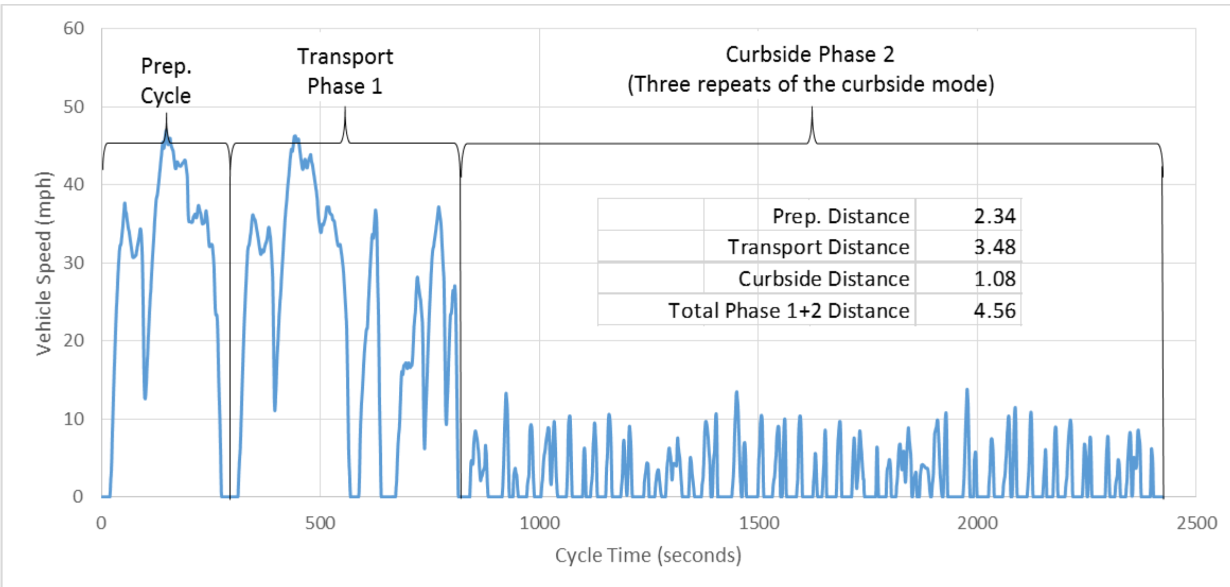


Figure B-4 Speed trace for AQMD refuse truck driving cycle

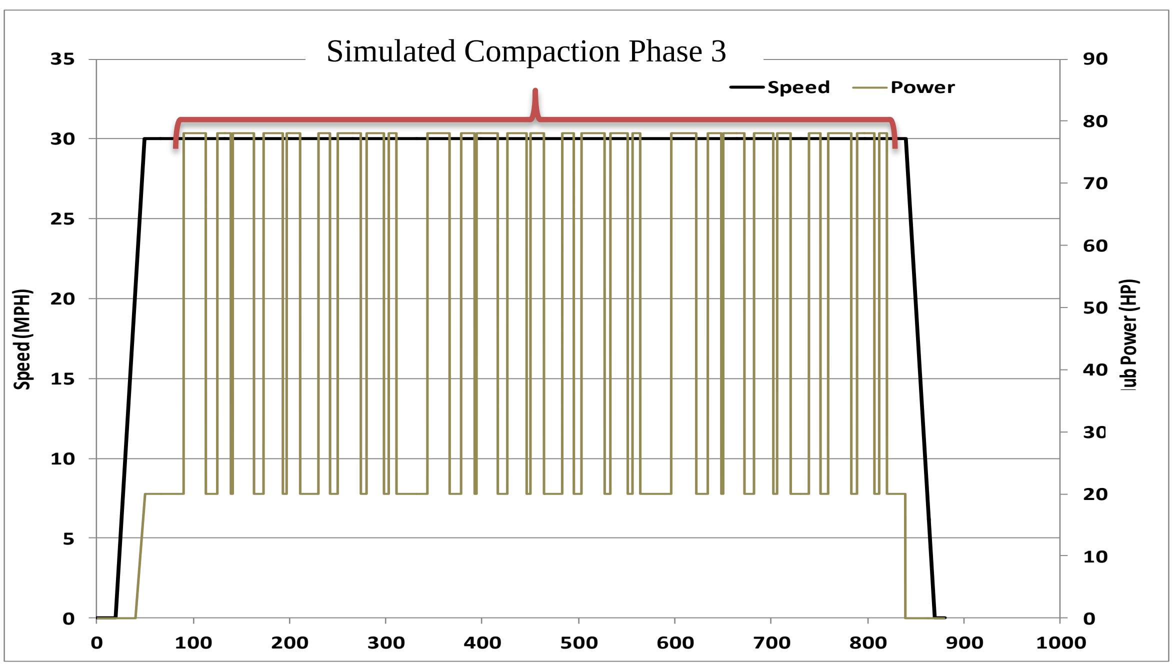


Figure B-5 Speed trace for AQMD refuse truck compaction cycle

Central Business District (CBD) Cycle

The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a "sawtooth" driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes. The following are characteristic parameters of the cycle:

- Duration: 560 s
- Average speed: 20.23 km/h
- Maximum speed: 32.18 km/h (20 mph)
- Driving distance: 3.22 km
- Average acceleration: 0.89 m/s^2
- Maximum acceleration: 1.79 m/s^2

Vehicle speed over the duration of the CBD cycle is shown in Figure A-1.

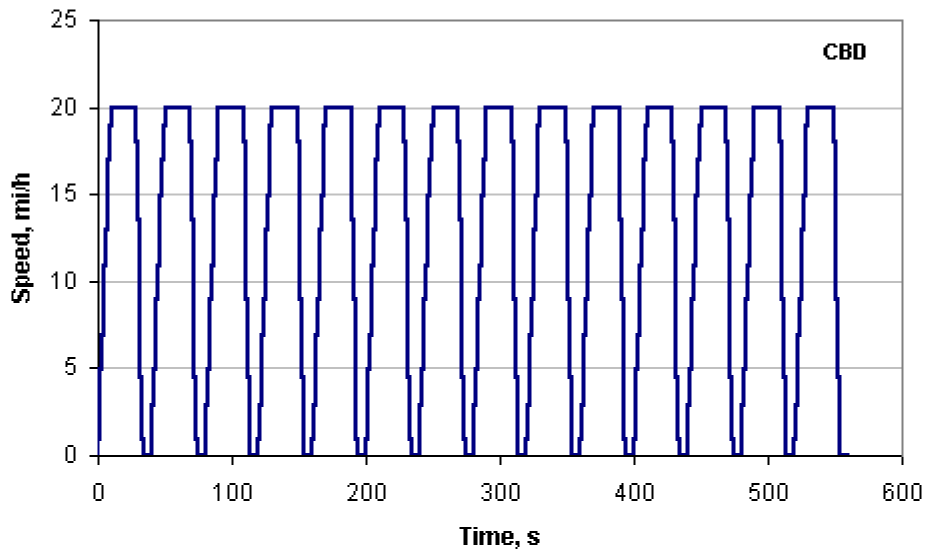


Figure B-6. CBD Driving Cycle

The standard CBD test cycle will be used for bus testing where three cycles will be combined for a triple CBD for a total sample time of 30 minutes. Performing the CBD cycle three times in one test allows for additional sample volumes to be collected for all batched type analysis (filters, DNPH, BETEX and N_2O). Preconditioning is defined as performing a previous triple CBD and a 20 minute soak to improve repeatability between hot repeats. Emissions analyses for gaseous emissions will also be collected over the triple CBD cycles. This cycle is shown in Figure A-2. The triple CBD cycle will be repeated in triplicate for repeatability metrics as described earlier.

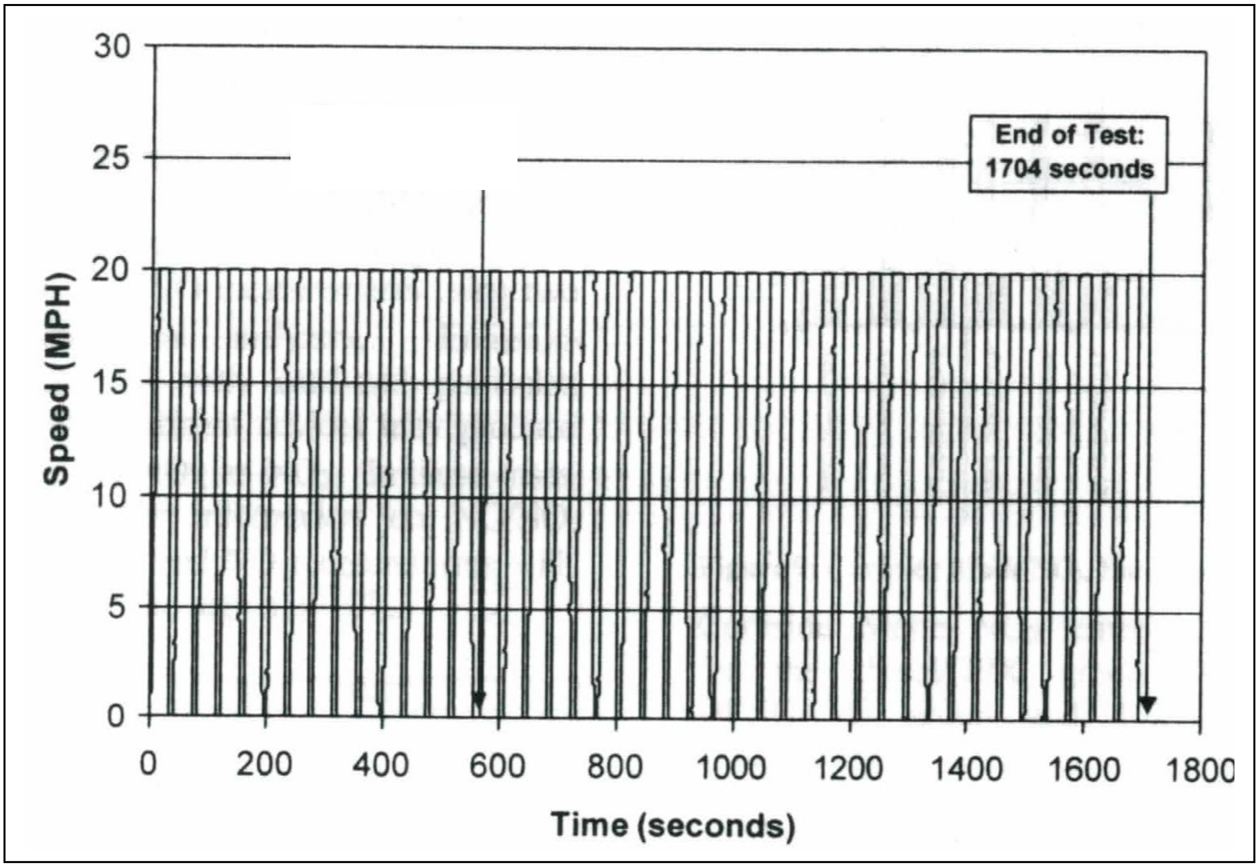


Figure B-7. Triple CBD Cycle

Appendix C. UCR Mobile Emission Laboratory

The approach used for measuring the emissions from a vehicle or an engine on a dynamometer is to connect UCR's heavy-duty mobile emission lab (MEL) to the total exhaust of the diesel engine. The details for sampling and measurement methods of mass emission rates from heavy-duty diesel engines are specified in Code of Federal Regulations (CFR): Protection of the Environment, Section 40, Part 1065. UCR's unique heavy-duty diesel mobile emissions laboratory (MEL) is designed and operated to meet those stringent specifications. MEL is a complex laboratory and a schematic of the major operating subsystems for MEL are shown in Figure C-1. The accuracy of MEL's measurements have been checked/verified against ARB's[10] and Southwest Research Institute's[11,12] heavy-duty diesel laboratories. MEL routinely measures Total Hydrocarbons (THC), Methane, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxides, and Particulate Matter (PM) emissions from diesel engines. Design capabilities and details of MEL are described in Cocker et al[1,13]. Samples can be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

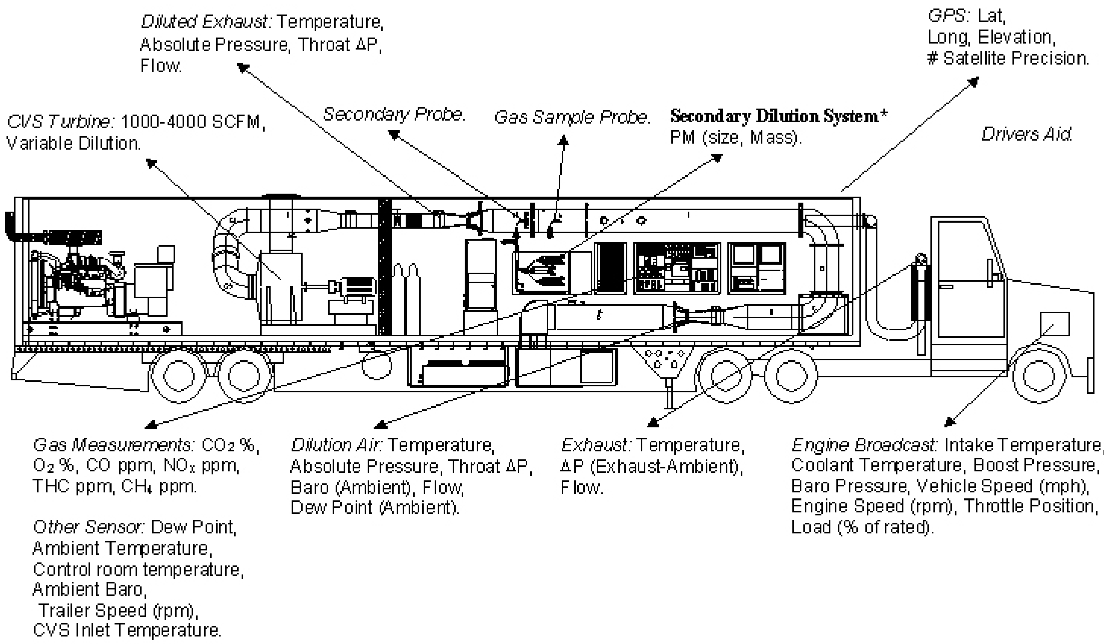


Figure C-1: Major Systems within UCR's Mobile Emission Lab (MEL)

[10] Cocker III, D. R., Shah, S. D., Johnson, K. C., Zhu, X., Miller, J. W., Norbeck, J. M., Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter, Environ. Sci. Technol. **2004**, 38, 6809-6816

[11] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., Measurement Allowance Project – On-Road Validation. Final Report to the Measurement Allowance steering Committee.

[12] Johnson, K.C., Durbin, T.D., Cocker, III, D.R., Miller, W.J., Bishnu, D.K., Maldonado, H., Moynahan, N., Ensfield, C., Laroo, C.A. (2009) On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle, Atmospheric Environment 43 (2009) 2877–2883

[13] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., *Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions*, Environmental Science and Technology. **2004**, 38, 2182-2189

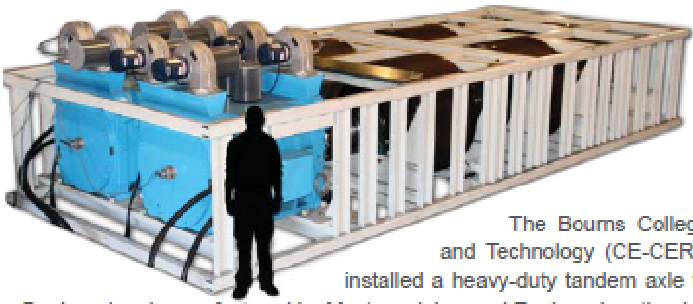
Appendix D. Heavy-Duty Chassis Dynamometer Laboratory

UCR's chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy duty vehicles, see Figure D-1. The design incorporates 48" rolls, axial loading to prevent tire slippage, 45,000 lb base inertial plus two large AC drive for achieving a range of inertias. The dyno has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horse power at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common.

The chassis dynamometer was designed to accurately perform the new CARB 4 mode cycle, urban dynamometer driving schedule (UDDS), refuse drive schedule (WHM), bus cycles (CBD), as well as any speed vs time trace that do not exceed the acceleration and deceleration rates. The load measurement uses state of the art sensing and is accurate to 0.05% FS and has a response time of less than 100 ms which is necessary for repeatable and accurate transient testing. The speed accuracy of the rolls is ± 0.01 mph and has acceleration accuracy of ± 0.02 mph/sec which are both measured digitally and thus easy to maintain their accuracy. The torque transducer is calibrated as per CFR 1065 and is a standard method used for determining accurate and reliable wheel loads.

Figure D-1. UCR's heavy duty chassis eddy current transient dynamometer

Mustang Advanced Engineering delivers a newly designed 48" Electric AC Heavy-Duty Truck Chassis Dynamometer with dual, direct-connected 300-hp AC motors to The University of California - Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT).



The science of measuring emissions from mobile and other sources has evolved significantly over the past several years. The most important changes in the nature of emissions measurement science has been a shift to examining emissions from diesel sources and to understanding emissions under in-use driving conditions.

The Bourns College of Engineering – Center for Environmental Research and Technology (CE-CERT) at The University of California Riverside has recently installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area. Designed and manufactured by Mustang Advanced Engineering, the development of this chassis dynamometer design was based on targeting vehicles in the medium to heavy-duty diesel vehicle range. Heavy-duty applications that can be tested at the facility include on-highway trucks, buses, waste haulers, yard tractors, and more - under test conditions representative of their specific in-use operations. The facility couples the new heavy-duty chassis dynamometer from Mustang Advanced Engineering with CE-CERT's Mobile Emissions Laboratory (MEL), to perform precise vehicle simulation and in-operation emissions measurements.

The first research conducted on the new facility will be a comparison of federally mandated diesel fuel formulas versus the stricter formulation required in California. The program calls for 10 heavy-duty trucks to be tested with several different fuels.

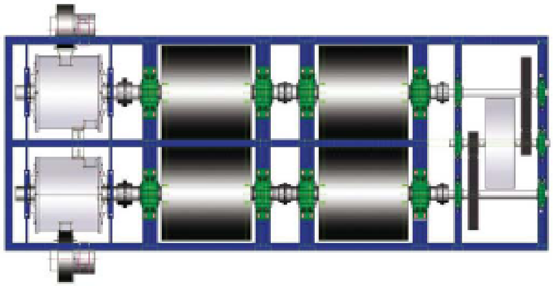
The new dynamometer will simulate on-road driving conditions for any big rig using its 48" precision rollers with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies the appropriate loading to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving conditions. An additional large inertia weight was incorporated into the dynamometer to increase the base mechanical inertia and enable the dynamometer to provide precise on-road simulation for a wide range of vehicle weights. The driver accelerates and decelerates according to a driving trace which specifies the speed and time over a wide range of vehicle simulation cycles. As the on-road driving conditions are being simulated on the dynamometer, emissions measurements will be collected with CE-CERT's Mobile Emissions Laboratory (MEL).

"This adds new capabilities in California that are only available at a limited number of facilities around the country," said Tom Durbin, who with J. Wayne Miller, are the principle investigators for the project. At both the state and federal levels, scientific requirements for emissions testing are trending away from steady state engine testing in favor of transient conditions found in typical driving, Durbin explained. "This addition will significantly expand our laboratory and measurement capabilities and help us continue our role as leading experts in the field of emissions research," said CE-CERT Director Matthew Barth.

CE-CERT's new heavy-duty chassis dynamometer will allow the testing of a variety of heavy vehicles under loaded and transient in-use conditions with corresponding emissions measurements. The dynamometer configuration is capable of meeting the inertia simulation range requirements of 10,000 to 80,000 lb for each of the cycles listed below. This includes acceleration rates up-to 6 mph/sec, as found in the UDDS Section D Drive Schedule and deceleration rates of up to 7 mph/sec as required for the WHM Refuse Drive Schedule. The dynamometer can also provide a load in excess of 600 HP @ 70 mph. The dynamometer also has the ability to continuously handle 200 Hp @ 15 mph for applications such as yard tractors.

The Dynamometer system is designed to meet the Heavy Duty Drive Schedules for diesel trucks in the weight range of 10,000 to 80,000 lb with acceleration rates for the following cycles:

- CARB HHDDT Cruise Mode Drive Schedule
- UDDS (Urban Dynamometer Drive Schedule)
- CARB 50 mph HHDDT Cruise Cycle
- HHDDT Transient Mode Drive Schedule
- WHM Refuse Drive Schedule
- Bus cycles such as, the CBD, OC Bus cycle, NY bus cycle
- In-use cycles for applications such as yard tractors.



"As part of our strategic plan, Mustang has developed a cost effective series of diesel, petroleum and hybrid certification grade dynamometer systems to address the needs of the global emissions and R&D market. There is a clear and present demand for a full performance cost effective dynamometer systems that offer all of the capabilities and confidence of a certification system at a price point that makes it no longer cost-prohibitive for organization to perform critical emissions studies, hybrid system calibration development, performance evaluation and other cutting edge research technologies. Researchers are in need of dynamometer systems to develop the next generation technologies which mimic the capabilities of the certification requirements, but at a fraction of the cost of a true certification system. That is what we are developing with this series of dynamometers and universities are lining up for them", said Executive Vice President, Donald Ganzhorn.

Appendix E. Additional Test Data and Results

This appendix includes some additional results not presented in the main report, but can be used to support the assumptions and decisions made for the results presented. Following Tables E-1 through E-4 are fuel sample analysis reports.

Table E-1 Average emission factors for all cycles (g/bhp-hr)

	Duration	Engine		Ave Modal Emission Factor (g/bhp-hr)							PM (mg/bhp-hr)		NOx Emissions (mg/bhp-hr)				
Trace	sec	bhp	bhp-hr	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M2	M3	M4	M5
CS_UDDS	1081	75.3	22.6	0.85	0.53	0.32	4.28	0.062	546.8		1.7	0.05	51.5	48.0	43.5	70.7	34.1
CS_DPT1	3049	31.8	26.9	1.15	0.56	0.59	5.25	0.090	627.0	0.64	0.7	0.02	22.5	28.6	14.0	20.9	2.7
UDDS	2122	69.7	41.1	0.05	0.04	0.00	1.51	-	548.9	0.32	1.1	0.06	16.6	18.0	13.9	20.9	2.6
RTC	2889	51.3	41.2	0.09	0.08	0.01	2.75	-	577.0	0.44	0.7	0.00	6.4	7.2	2.2	28.6	4.9
DPT1	3049	27.7	23.5	0.37	0.26	0.10	2.35	-	649.8	0.66	0.9	0.07	4.2	0.0	2.0	9.2	1.4
DPT2	3365	36.5	34.1	0.20	0.16	0.05	2.01	0.027	597.0	0.47	0.5	0.10	16.6	17.2	12.6	21.6	4.5
DPT3	4228	74.9	87.9	0.49	0.33	0.17	1.34	0.024	549.3	0.37	1.0	0.01	18.4	20.8	14.1	23.7	4.1
CBD	560	76.2	11.8	0.16	0.11	0.05	2.73	0.034	576.1	0.94	0.9	0.04	-3.3	0.4	1.2	3.1	-0.2
Tunnel	1134	70.5	22.2	-0.01	0.00	-0.02	-0.07		0.5	0.03	0.4	0.04	0.2	2.6	1.0	1.4	0.6

Table E-2 Standard deviation of the emission factors for all cycles (g/bhp-hr)

	Duration	Engine		Stdev Modal Emission Factor (g/bhp-hr)							PM (mg/bhp-hr)		NOx Emissions (mg/bhp-hr)				
Trace	sec	bhp	bhp-hr	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M1	M1	M1	M1
CS_UDDS	0.0	0.2	0.1	0.07	0.04	0.03	0.39	-	14.1		0.9	0.01	26.9	32.3	11.7	17.5	29.2
CS_DPT1	0.0	0.1	0.1	0.52	0.08	0.44	0.71	-	2.9	0.09	0.4	0.07	24.4	19.2	8.7	4.7	0.9
UDDS	0.0	1.1	0.6	0.01	0.01	0.01	0.13	-	9.1	0.01	0.5	0.03	20.1	21.6	15.1	22.8	3.5
RTC	0.0	0.4	0.3	0.05	0.03	0.03	0.44	-	8.1	0.08	0.4	0.10	5.1	2.9	1.3	45.9	8.6
DPT1	0.0	1.1	0.9	0.20	0.13	0.07	0.39	-	8.3	0.12	0.2	0.02	4.1	7.8	1.9	2.8	0.4
DPT2	0.0	0.7	0.6	0.03	0.01	0.01	0.06	0.004	13.7	0.02	0.1	0.01	10.8	10.7	6.3	12.5	0.8
DPT3	0.0	0.3	0.4	0.03	0.02	0.01	0.23	0.003	7.7	0.10	0.9	0.01	4.7	6.5	3.6	6.5	1.9
CBD	0.0	0.8	0.1	0.02	0.02	0.01	0.75	0.012	25.9	0.24	0.5	0.01	6.3	1.0	1.3	1.5	0.3
Tunnel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table E-3 Average emission factors for all cycles (g/mi)

	Vehicle			Ave Modal Emission Factor (g/mi)							PM (mg/mi)		NOx Emissions (mg/mi)				
Trace	sec	bhp	mi	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M1	M1	M1	M1
CS_UDDS	1081	75.3	5.2	3.70	2.31	1.40	18.5	0.27	2367	-	7.3	0.21	223	208	189	306	164
CS_DPT1	3049	31.8	5.8	5.29	2.58	2.74	24.3	0.41	2895	2.98	3.1	0.10	104	132	65	96	13
UDDS	2122	69.7	11.2	0.17	0.16	0.01	5.5	-	2005	1.19	3.9	0.20	61	66	51	77	10
RTC	2889	51.3	4.4	0.82	0.74	0.09	25.4	-	5348	4.09	6.5	0.02	61	67	20	274	47
DPT1	3049	27.7	5.9	1.45	1.04	0.41	9.4	-	2589	2.64	3.5	0.29	17	-1	8	37	6
DPT2	3365	36.5	9.1	0.77	0.58	0.19	7.5	0.10	2236	1.77	1.7	0.39	63	65	48	81	17
DPT3	4228	74.9	28.1	1.54	1.02	0.53	4.2	0.07	1718	1.16	3.2	0.05	58	65	44	74	13
CBD	560	76.2	2.1	0.89	0.64	0.25	15.3	0.19	3226	5.27	5.3	0.23	-19	2	7	17	0
Tunnel	1134	70.5	6.0	-0.07	0.02	-0.08	-0.3	-	1.9	0.10	1.6	0.14	1	10	4	5	2

Table E-4 Standard deviation of the emission factors for all cycles (g/mi)

	Vehicle			Stdev Modal Emission Factor (g/mi)							PM (mg/mi)		NOx Emissions (mg/mi)				
Trace	sec	bhp	bhp-hr	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M1	M1	M1	M1
CS_UDDS	0	0.2	0.1	0.22	0.13	0.09	1.4	-	93	-	4.2	0.06	118	141	53	79	156
CS_DPT1	0	0.1	0.0	2.37	0.37	2.02	3.4	-	3	0.39	1.6	0.35	112	88	40	22	4
UDDS	0	1.1	0.1	0.05	0.03	0.02	0.4	-	8	0.06	2.0	0.12	75	81	56	85	13
RTC	0	0.4	0.1	0.44	0.26	0.23	3.4	-	146	0.78	3.2	0.96	49	30	12	444	83
DPT1	0	1.1	0.1	0.77	0.50	0.28	2.0	-	88	0.61	0.6	0.08	17	31	7	11	2
DPT2	0	0.7	0.1	0.11	0.06	0.05	0.3	0.01	16	0.11	0.3	0.04	41	41	24	47	3
DPT3	0	0.3	0.1	0.08	0.04	0.04	0.7	0.01	27	0.31	2.8	0.04	14	20	11	20	6
CBD	0	0.8	0.0	0.14	0.10	0.05	4.4	0.07	187	1.44	3.1	0.04	36	5	7	9	0
Tunnel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Atmospheric Analysis & Consulting, Inc.

Laboratory Analysis Report
ASTM-D3588 (BTU and F-Factor)

CLIENT	University of Riverside	**SAMPLING DATE**	11/20/2015
PROJECT NO.	160033	**ANALYSIS DATE**	1/11/2016

	Client ID:	CNG 1501	
	AAC ID:	160033-86526	
	Component	**Mole %**	**Weight %**
FIXED GASES	H_2	0.00	0.00
	O_2	0.00	0.00
	N_2	0.63	1.04
	CO	0.00	0.00
	CO_2	0.35	0.90
	CH_4	94.65	89.77
	He	NM	NM
	Ar	NM	NM
HYDROCARBONS	C_2 (as Ethane)	3.8675	6.8752
	C_3 (as Propane)	0.4110	1.0715
	C_4 (as Butane)	0.0757	0.2602
	C_5 (as Pentane)	0.0112	0.0480
	C_6 (as Hexane)	0.0025	0.0126
	C_{6+} (as Hexane)	0.0032	0.0163
TRS	TRS as H2S	NM	NM
H2O	Moisture content	NM	NM

All results have been normalized to 100% on a dry weight basis.

Fuel Gas Specifications			
Atomic Breakdown - (scf/lb) / %			
Carbon (C)	74.1	*HHV Btu/lb*	23286
Hydrogen (H)	24.2	*LHV Btu/lb*	20987
Oxygen (O)	0.7	*HHV Btu/dscf*	1038
Nitrogen (N)	1.0	*LHV Btu/dscf*	936
Helium (He)	0.00	*F-Factor*	8645
Argon (Ar)	0.00	*Relative Denisty*	0.5841
Sulfur (S)	0.00	*C2-C6+ Weight %*	8.2837
Motor Octane Number	131.32	*MW lb/lb-mole*	16.915
		Methane Number	94.17

Marcus Hueppe
Laboratory Director

1534 Eastman Ave., Ste. A • Ventura, • CA 93003 www.aaclab.com • (805) 650-1642 • FAX (805) 650-1644

Atmospheric Analysis & Consulting, Inc.

Quality Control/Quality Assurance Report

Date Analyzed : **01/11/2016**
Analyst : **DJ**
Units : **%**

Instrument ID : **TCD#1**
Calb Date : **01/06/2016**
Reporting Limit : **0.1%**

I - Opening Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
CCV	Spike Conc	9.5	10.0	20.4	10.2	10.1	10.2
	Result	9.4	10.4	20.6	10.4	10.0	10.1
	% Rec *	98.8	103.3	100.8	101.6	99.4	98.8

II - Method Blank - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
MB	Concentration	ND	ND	ND	ND	ND	ND

III - Laboratory Control Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
Lab Control Standards	Sample Conc	0.0	0.0	0.0	0.0	0.0	0.0
	Spike Conc	9.5	10.0	20.4	10.2	10.1	10.2
	LCS Result	8.8	9.9	19.9	10.3	9.8	9.9
	LCSD Result	9.2	10.4	21.0	10.8	10.4	10.5
	LCS % Rec *	92.7	98.2	97.5	100.3	96.8	96.5
	LCSD % Rec *	96.9	104.1	102.9	106.1	103.4	102.5
	% RPD ***	4.5	5.8	5.4	5.6	6.7	6.0

IV - Sample & Sample Duplicate - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
151755-86178	Sample	0.0	12.2	44.2	0.0	0.0	0.0
	Sample Dup	0.0	12.2	44.1	0.0	0.0	0.0
	Mean	0.0	12.2	44.1	0.0	0.0	0.0
	% RPD ***	0.0	0.2	0.3	0.0	0.0	0.0

V - Matrix Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	H_2	N_2	CO_2	CH_4	CO
151755-86178	Sample Conc	0.0	22.1	0.0	0.0	0.0
	Spike Conc	9.5	9.9	10.2	10.1	10.2
	MS Result	9.3	33.1	10.7	10.1	10.2
	MSD Result	8.6	33.0	10.3	9.6	9.7
	MS % Rec **	98.1	110.9	104.2	100.4	99.9
	MSD % Rec **	90.7	109.4	101.1	95.2	94.9
	% RPD ***	7.9	1.3	3.0	5.3	5.0

VI - Closing Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
CCV	Spike Conc	9.5	10.0	20.4	10.2	10.1	10.2
	Result	9.5	10.8	21.5	10.9	10.4	10.5
	% Rec *	100.5	107.7	104.9	106.3	103.3	102.4

** Must be 85-115%*
*** Must be 75-125%*
**** Must be < 25%*
ND = Not Detected
<RL = less than Reporting Limit

Marcus Hueppe
Laboratory Director

Atmospheric Analysis & Consulting, Inc.

Quality Control/Quality Assurance Report

Date Analyzed : **01/11/2015**
Analyst : **DJ**
Units : **ppmv**

Instrument ID : **FID #3**
Calb Date : **01/06/16**
Reporting Limit : **0.5 ppmv**

I - Opening Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
CCV	Spike Conc	102.0	98.6	95.2	100.8	99.6	98.8
	Result	105.4	103.9	100.1	105.8	104.5	104.7
	% Rec *	103.3	105.3	105.1	104.9	104.9	106.0

II - Method Blank - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
MB	Concentration	ND	ND	ND	ND	ND	ND

III - Laboratory Control Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
Lab Control Standards	Sample Conc	0.0	0.0	0.0	0.0	0.0	0.0
	Spike Conc	102.0	98.6	95.2	100.8	99.6	98.8
	LCS Result	101.2	99.8	96.9	102.3	101.8	102.8
	LCSD Result	102.4	101.4	98.2	103.9	104.2	108.0
	LCS % Rec *	99.2	101.2	101.8	101.5	102.2	104.1
	LCSD % Rec *	100.4	102.9	103.2	103.1	104.6	109.4
	% RPD ***	1.2	1.6	1.3	1.6	2.3	5.0

IV - Sample & Sample Duplicate - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
151755-86178	Sample	2.6	0.0	0.0	0.0	0.0	0.0
	Sample Dup	2.6	0.0	0.0	0.0	0.0	0.0
	Mean	2.6	0.0	0.0	0.0	0.0	0.0
	% RPD ***	0.8	0.0	0.0	0.0	0.0	0.0

V - Matrix Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
151755-86178	Sample Conc	1.3	0.0	0.0	0.0	0.0	0.0
	Spike Conc	51.0	49.3	47.6	50.4	49.8	49.4
	MS Result	53.4	50.2	49.2	51.9	51.6	52.4
	MSD Result	53.1	50.9	49.3	52.2	55.1	53.3
	MS % Rec **	102.2	101.9	103.5	103.0	103.6	106.1
	MSD % Rec **	101.5	103.2	103.6	103.7	110.7	107.8
	% RPD ***	0.7	1.3	0.2	0.6	6.6	1.6

VI - Closing Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
CCV	Spike Conc	102.0	98.6	95.2	100.8	99.6	98.8
	Result	101.3	99.5	96.4	101.3	99.3	98.4
	% Rec *	99.3	100.9	101.2	100.5	99.7	99.6

** Must be 85-115%*
*** Must be 75-125%*
**** Must be < 25%*
ND = Not Detected
<RL = less than Reporting Limit

Marcus Hueppe
Laboratory Director

Appendix F. Engine certification data, labels, and upgrades

This appendix includes the engine executive order Figure F-1 as listed on the ARB website for the family number listed on the engine name plate see Figure F-2 and F-3, Family number ECEXH0540LBH. The ISL G NZ certification is provided in the recently released documents as presented in Figure F-4, 5, and 6.

MODEL YEAR	ENGINE FAMILY	ENGINE SIZES (L)	FUEL TYPE [1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS [2]	ECS & SPECIAL FEATURES [3]	DIAGNOSTIC [6]
2014	ECEXH0540LBH	8.9	CNG/LNG	Diesel	HHDD	TBI, TC, CAC, ECM, EGR, TWC, HO2S	EMD

PRIMARY ENGINE'S IDLE EMISSIONS CONTROL [5]	ADDITIONAL IDLE EMISSIONS CONTROL [5]
EXEMPT	N/A

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
8.9	See attachment for engine models and ratings

* =not applicable; **GVWR**=gross vehicle weight rating; **13 CCR xyz**=Title 13, California Code of Regulations, Section xyz; **40 CFR 86.abc**=Title 40, Code of Federal Regulations, Section 86.abc; **L**=liter; **hp**=horsepower; **kw**=kilowatt; **hr**=hour;

[1] **CNG/LNG**=compressed/liquefied natural gas; **LPG**=liquefied petroleum gas; **E85**=85% ethanol fuel; **MF**=multi fuel a.k.a. **BF**=bi fuel; **DF**=dual fuel; **FF**=flexible fuel;

[2] **L/M/H HDD**=light/medium/heavy heavy-duty diesel; **UB**=urban bus; **HDO**=heavy duty Otto;

[3] **ECS**=emission control system; **TWC/OC**=three-way/oxidizing catalyst; **NAC**=NOx adsorption catalyst; **SCR-U / SCR-N**=selective catalytic reduction – urea / – ammonia; **WU (prefix)** =warm-up catalyst; **DPF**=diesel particulate filter; **PTOX**=periodic trap oxidizer; **HO2S/O2S**=heated/oxygen sensor; **HAFS/AFS**=heated/air-fuel-ratio sensor (a.k.a., universal or linear oxygen sensor); **TBI**=throttle body fuel injection; **SFI/MFI**=sequential/multi port fuel injection; **DGI**=direct gasoline injection; **GCARB**=gaseous carburetor; **IDI/DDI**=indirect/direct diesel injection; **TC/SC**=turbo/super charger; **CAC**=charge air cooler; **EGR / EGR-C**=exhaust gas recirculation / cooled EGR; **PAIR/AIR**=pulsed/secondary air injection; **SPL**=smoke puff limiter; **ECM/PCM**=engine/powertrain control module; **EM**=engine modification; **2 (prefix)**=parallel; **(2) (suffix)**=in series;

[5] **ESS**=engine shutdown system (per 13 CCR 1956.8(a)(6)(A)(1); **30g**=30 g/hr NOx (per 13 CCR 1956.8(a)(6)(C); **APS** =internal combustion auxiliary power system; **ALT**=alternative method (per 13 CCR 1956.8(a)(6)(D); **Exempt**=exempted per 13 CCR 1956.8(a)(6)(B) or for CNG/LNG fuel systems; **N/A**=not applicable (e.g., Otto engines and vehicles);

[6] **EMD**=engine manufacturer diagnostic system (13 CCR 1971); **OBD**=on-board diagnostic system (13 CCR 1971.1);

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.8; 2) the EURO and NTE limits under the applicable California exhaust emission standards and test procedures for heavy-duty diesel engines and vehicles (Test Procedures); and 3) the corresponding certification levels, for this engine family. "Diesel" CO, SET and NTE certification compliance may have been demonstrated by the manufacturer as provided under the applicable Test Procedures in lieu of testing. (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR 1956.8 are in parentheses.). [4]

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.20	0.20	*	*	15.5	15.5	0.01	0.01	*	*
FEL	*	*			*	*	*	*	*	*	*	*
CERT	0.09	0.08	0.13	0.01	*	*	14.2	11.6	0.002	0.001	*	*
NTE	0.21		0.30		*		19.4		0.02		*	

[4] **g/bhp-hr**=grams per brake horsepower-hour; **FTP**=Federal Test Procedure; **SET**= Supplemental emissions testing; **NTE**=Not-to-Exceed; **STD**=standard or emission test cap; **FEL**=family emission limit; **CERT**=certification level; **NMHC/HC**=non-methane/hydrocarbon; **NOx**=oxides of nitrogen; **CO**=carbon monoxide; **PM**=particulate matter; **HCHO**=formaldehyde

Engine Family	1.Engine Code	2.Engine Model	3.BHP@RPM (SAE Gross)	4.Fuel Rate: mm/stroke @ peak HP (for diesel only)	5.Fuel Rate: (lbs/hr) @ peak HP (for diesels only)	6.Torque @ RPM (SEA Gross)	7.Fuel Rate: mm/stroke@peak torque	8.Fuel Rate: (lbs/hr)@peak torque	9.Emission Control Device Per SAE J1930
ECEXH0540LBH	3519;FR93287	ISL G 250	250@2200	N/A	N/A	730@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR93284	ISL G 260	260@2200	N/A	N/A	660@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR93282	ISL G 280	280@2200	N/A	N/A	900@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR93279	ISL G 300	300@2100	N/A	N/A	860@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR93276	ISL G 320	320@2100	N/A	N/A	1000@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR94391	ISL G 250	250@2200	N/A	N/A	730@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR94388	ISL G 260	260@2200	N/A	N/A	660@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR94386	ISL G 280	280@2200	N/A	N/A	900@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR94383	ISL G 300	300@2100	N/A	N/A	860@1300	N/A	N/A	H02S, PCM, TWC,
ECEXH0540LBH	3519;FR94380	ISL G 320	320@2100	N/A	N/A	1000@1300	N/A	N/A	H02S, PCM, TWC,

Figure F-1 Engine certification order for the ISL G (not ISL G NZ) NG engine (ARB source)

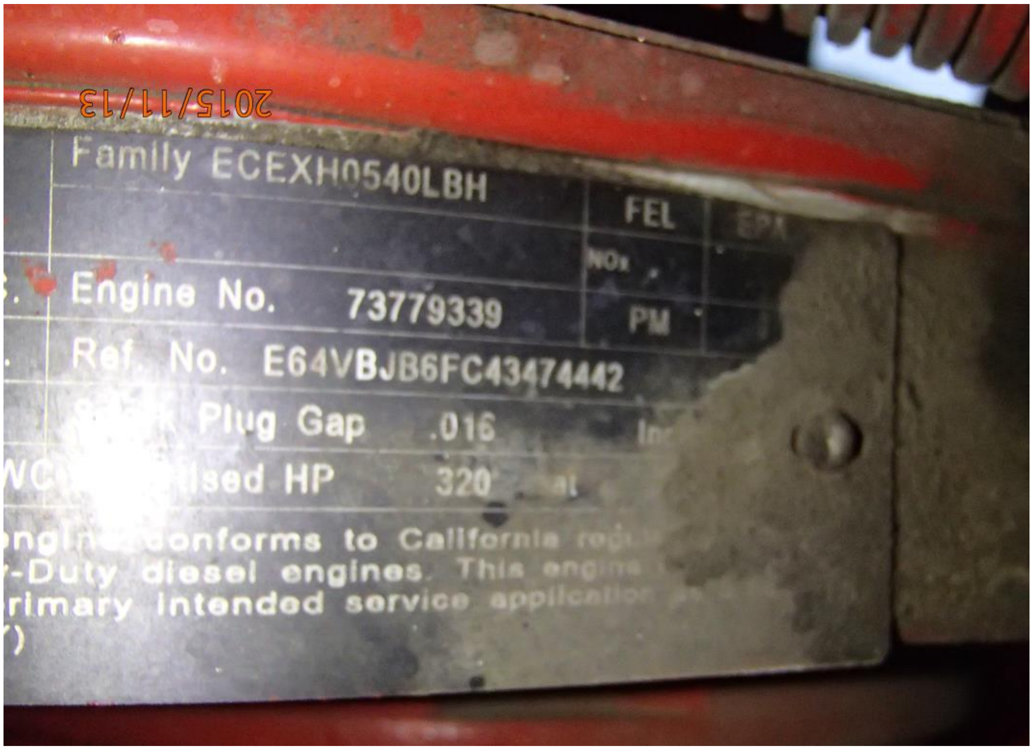


Figure F-2 Engine label for the ISL G NZ 320 NG engine

Figure F-3 Engine label for the ISL G NZ 320 NG engine

ARB EPA

ENGINE MODEL	ADVERTISED HP(KW) @ RPM	PEAK TORQUE LB-FT @ RPM	GOVERNED SPEED
ISL G NZ 320	320 (239) @ 2000	1000 (1356) @ 1300	2200 RPM
ISL G NZ 300	300 (224) @ 2100	860 (1166) @ 1300	2200 RPM
ISL G NZ 280	280 (209) @ 2000	900 (1220) @ 1300	2200 RPM
ISL G NZ 260	260 (194) @ 2200	660 (895) @ 1300	2200 RPM
ISL G NZ 250	250 (186) @ 2200	730 (990) @ 1300	2200 RPM

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.02	0.02	*	*	15.5	15.5	0.01	0.01	*	*
CERT	0.01	0.000	0.01	0.004	*	*	1.5	0.3	0.001	0.000	*	*
NTE	0.21		0.03		*		19.4		0.02		*	

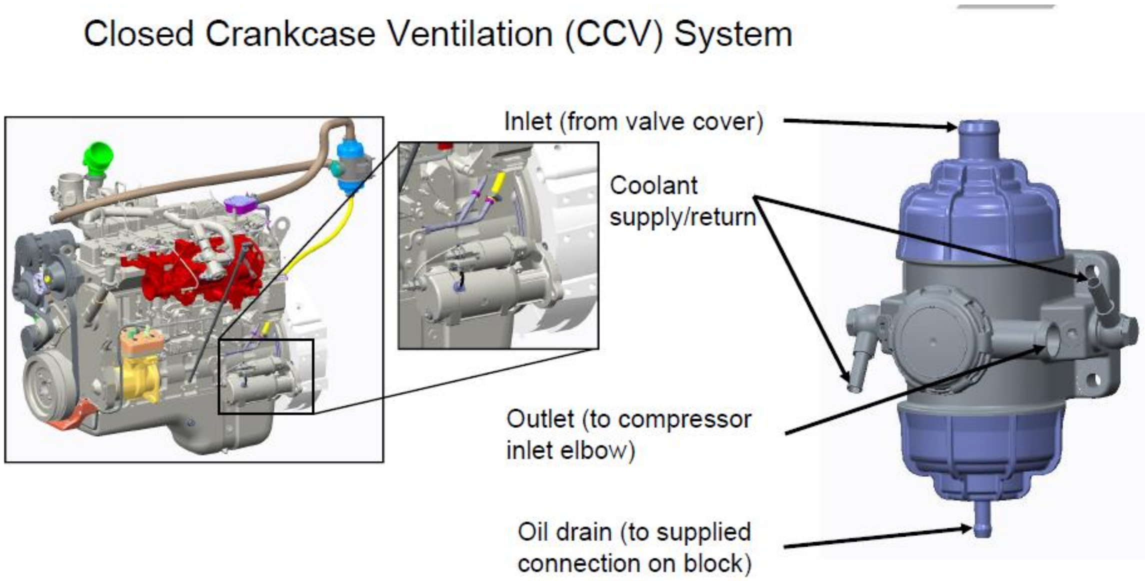
[4] g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET= Supplemental emissions testing; NTE=Not-to-Exceed; STD=standard or emission test cap; FEL=family emission limit; CERT=certification level; NMHC/HC=non-methane/hydrocarbon; NOx=oxides of nitrogen; CO=carbon monoxide; PM=particulate matter; HCHO=formaldehyde

in g/bhp-hr	EPA CERTIFICATE OF CONFORMITY		PRIMARY INTENDED SERVICE CLASS	
	*		VOCATIONAL	
	CO_2		CH_4	N_2O
	FTP	SET		
STD	555	*	0.10	0.10
FCL	476	*	*	*
FEL	490	*	0.65	*
CERT	465	*	0.56	0.02

[4] g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET=Supplemental emissions testing; STD = standard or emission test cap; FEL=family emission limit; FCL=family certification level; CERT=certification level; CO_2=carbon dioxide; CH_4=methane; N_2O=nitrous oxide; VOCATIONAL=vocational engine; TRACTOR=tractor engine

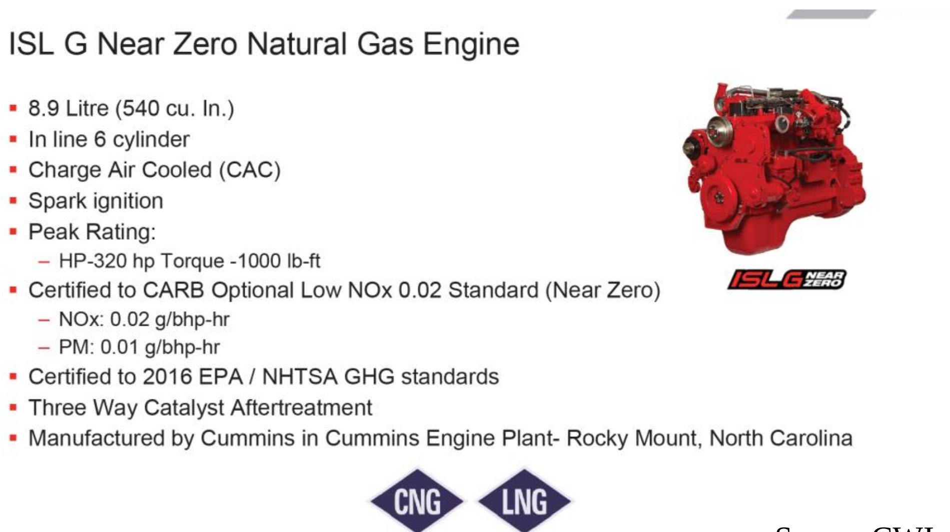
Source CWI
Fam# GCEXH0540LBH

Figure F-4 2016 ISL G NZ certification executive order with engine ratings (ARB and EPA)



Source CWI

Figure F-5 Cummins methane blow by capture improvement



Source CWI

Figure F-6 Cummins specifications for the ISL G NZ

Changes from ISL G EPA 2013

- **Certification**
  - new Agency Approval (AP) option
- **ECM Calibration**
  - 0.02g NOx calibration
  - Delegated Assembly protected via catalyst / ECM connection
- **Three Way Catalyst (TWC)**
  - Same as ISX12 G and ISL G Euro VI
  - Has extra mid bed temperature sensor that must be added to OEM harness
- **New Closed Crankcase Ventilation (CCV) System**
  - Remote mount CCV filter – to be installed by OEMs
  - Similar to ISL G Euro VI, but with coolant heating (same as ISB6.7 G)
  - Requires OEM installed air/oil and coolant plumbing to and from the engine
- **Crankcase Pressure Sensor**
  - New for diagnostic and OBD purposes

Source CWI

Figure F-7 ISL G NZ emission enhancements

Appendix G. Coastdown methods

Road load coefficients are important where at 65 mph the aerodynamic term accounts for 53% of the resisting force, rolling resistance 32%, driveline losses 6% and auxiliary loads at 9%. These load fractions vary with speed and the square of the speed where a properly configured dynamometer is needed to simulate the loads from 0 to 70 mph. The method for determining coastdown coefficients was published and evaluated as part of a study submitted to the South Coast Air Quality Management District[14]. Typical coastdown procedures assume that vehicle loading force is a function of vehicle speed, drag coefficient, frontal area and tire rolling resistance coefficient and takes the form of equation 1:

$$M\frac{dV}{dt} = \frac{1}{2}\rho A C_D V^2 + \mu Mgcos(\theta) + Mgsin(\theta) \qquad \text{(Equation 1)}$$

Where:
M = mass of vehicle in lb (tractor + payload + trailer+ 125lb/tire)
ρ = density of air in kg/m^3.
A = frontal area of vehicle in square feet, see Figure G-1 below
C_D = aerodynamic drag coefficient (unit less).
V = speed vehicle is traveling in mph.
μ = tire rolling resistance coefficient (unit less).
g = acceleration due to gravity = 32.1740 ft/sec^2.
θ = angle of inclination of the road grade in degrees (this becomes zero).

Assuming that the vehicle loading is characteristic of this equation, speed-time data collected during the coastdown test can be used with static measurements (ZET/NZET mass, air density, frontal area, and grade) to solve for drag coefficient (C_d) and tire rolling resistance coefficient (μ). The frontal area is measured based on the method described in Figure G-1 below. However, experience performing in-use coastdowns is complex and requires grades of less than 0.5% over miles of distance, average wind speeds < 10 mph ± 2.3 mph gusts and < 5 mph cross wind[15]. As such, performing in-use coastdowns in CA where grade and wind are unpredictable are unreliable where a calculated approach is more consistent and appropriate. Additionally vehicles equipped with automatic transmissions have shown that on-road loading is also affected by the characteristics of the vehicle transmission, especially when reverse pumping losses at low speed begin to dominate.

UCR's and others recommend a road load determination method that uses a characteristic coastdown equation, with a measured vehicle frontal area (per SAE J1263 measurement recommendations), a tire rolling resistance μ, and a coefficient of drag (Cd) as listed in Table G-1. If low rolling resistant tires are used then the fuel savings can be employed with a slightly improved coefficient as listed. Similarly if an aerodynamic tractor design is utilized (ie a certified SmartWay design) then a lower drag coefficient can be selected. Table G-1 lists the

[14] Draft Test Plan Re: SCAQMD RFP#P2011-6, "In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines", October 2011
[15] EPA Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium and heavy duty engines and vehicles, Office of Transportation and Air Quality, August 2011 (Page 3-7) and J1263 coast down procedure for fuel economy measurements

coefficients to use based on different ZET/NZET configurations. Once the coefficients are selected then they can be used in the above equation to calculate coastdown times to be used for calculating the A, B, C coefficients in Equation 2 for the dynamometer operation parameters. From these equations calculate the coastdown times from based on the coefficients in Table G-1 as shown in Table G-2 (65,000 lb, ustd, Cdstd and Table G-1). From Table G-2 one can plot the force (lb) vs average speed bin to get the ABC coefficients for the chassis dynamometer (see Figure G-2). These are the coefficients to enter into the chassis dynamometer then validate via the details of Appendix C. Repeat process until validation criteria is met. Typically one or two iterations is needed to meet the validation criteria.

Table G-1 Constants and parameters for Class 8 heavy duty trucks

Variable	Value	Description
θ	0	no grade in these tests
ρ	1.202	standard air density kg/m^3
μ_{std}	0.00710	standard tires
μ_{adv}	0.00696	low rolling resistant tires
C_{D_std}	0.750	for non-SmartWay tractor
C_{D_adv}	0.712	for SmartWay tractor
g	9.806	nominal value m/sec^2
M	Varies	mass: final test weight kg

[1] The tire rolling resistance, μ, for low rolling resistant tires shows a 1-2% savings (ref SmartWay). As such utilize 0.00686 fpr low rolling resistant tires. In this document the tractors may vary, but the trailers will be assumed similar. As such, if the tractor utilizes the certified SmartWay tractor type then coefficient of drag can be reduced by up to 10% (5% fuel savings) depending on the technology. As such in this guidance document utilize the Cd_adv for SmartWay tractors and Cd_std for non-SmartWay tractors. Additionally, for reference other vocations show higher Cd's, such as the C_D = 0.79 for buses and 0.80 for refuse trucks. Nominal value of gravity is used in this document where actual value can be found by following 40CFR 1065.630 or at http://www.ngs.noaa.gov

$$\frac{dV}{dt} = \frac{1}{2}\frac{\rho A C_D V^2}{M} + \mu g cos(\theta) + \ g sin(\theta) \qquad \text{(Equation 2)}$$

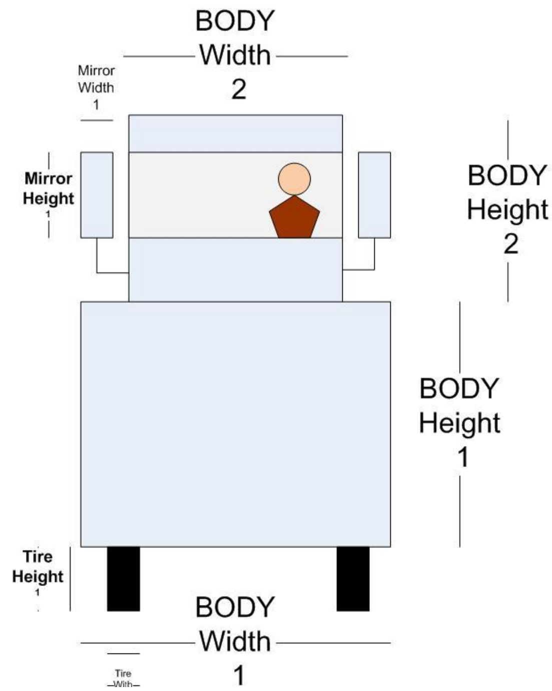


Figure G-1 Vehicle frontal area dimensions method

Using Equation 2 (solution for $\frac{dV}{dt}$ or deceleration), one can calculate the deceleration for each average speed bin (60, 50, … down to 20 mph), see Table G-2. From the deceleration time one can calculate the desired time which is the target for the coast down simulation on the chassis dynamometer. Using the final test weight (M), the total simulated force can be calculated using Equation 1 at each speed bin, see values Table G-2. Plot the simulated force (lb) on the y-axis vs truck speed (mph) on the x-axis. Using a best fit polynomial of order two, calculate the polynomial coefficients A (0th order term), B (1st order term), and C (2nd order term), see Figure G-2. Enter these ABCs into your chassis dynamometer and verify the coast down times match your desired coast down times to within 5%.

The calculation approach is consistent and has proven very reliable for chassis testing heavy duty vehicle and has been used for years by UCR and others. For detailed evaluation of aerodynamic modifications and body styles, UCR recommends investing the time perform in-use coastdowns where sufficient program resources will be needed as per 40 CFR Part 1066, SAE J2263, and J1263.

Table G-2 Desired coastdown times for a Class 8 truck with standard components

		Desired				
Data Point	Avg Speed MPH	Calc Time sec	Decel MPH/Sec	Decel ft/sec^2	Decel Gs	Force lb
65-55	60	25.67	0.38954	0.57	0.018	1154
55-45	50	31.44	0.31806	0.47	0.014	942
45-35	40	38.51	0.25965	0.38	0.012	769
35-25	30	46.68	0.21422	0.31	0.010	635
25-15	20	55.02	0.18177	0.27	0.008	539

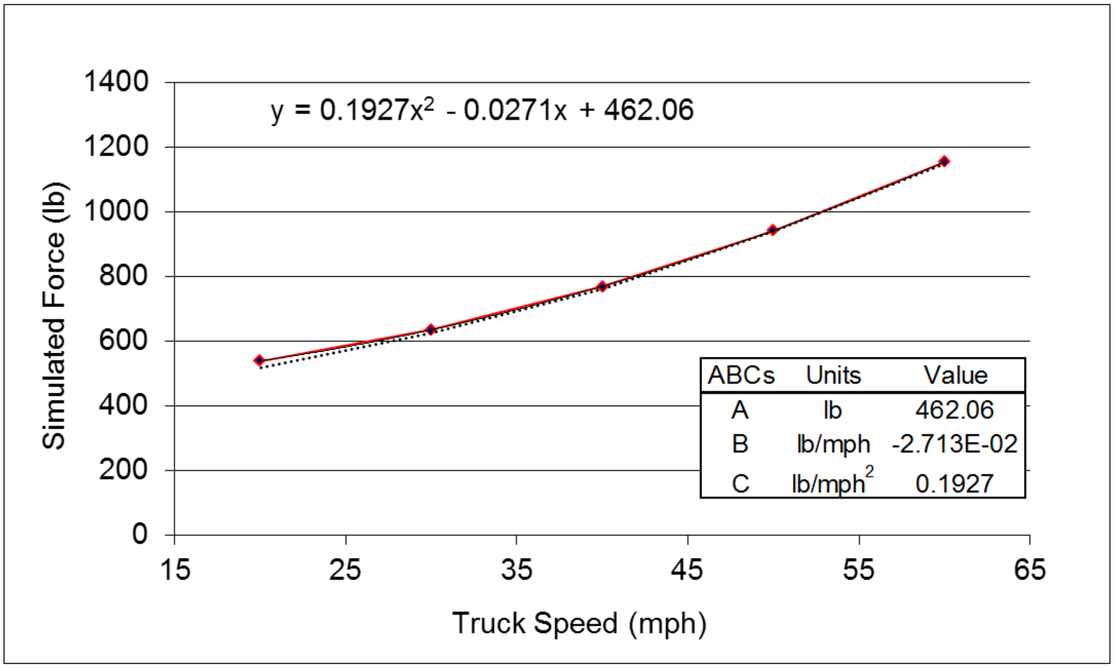


Figure G-2 Resulting ABCs based on Table G-2 results